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ELECTRICAL RESISTIVITY OF FINISH GRADING MATERIALS FOR TRANSFORMER AND SWITCHING STATIONS

Report No 91-207-K

C.B.H. Cragg, Senior Engineer
A.G. Vorauer, Engineer
Soil Sciences Section
Civil Research Department

ABSTRACT

The electrical resistivity of the surface grading material is of critical importance to the safety of workers within transformer and switching stations. This report describes a laboratory test recently developed to evaluate the electrical resistivity of surface grading materials. The philosophy of the test, its limitations and its relation to work done by others is described. Tests on surface materials from existing transformer stations and on potential new fill sources are presented, which show that existing specifications may be adjusted to include coarse concrete or HL8 asphalt aggregates.

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To Mr. J.L. Bender
Manager
Transmission Station Design
Design and Development - Transmission

ELECTRICAL RESISTIVITY OF FINISH GRADING MATERIALS FOR TRANSFORMER AND SWITCHING STATIONS

1.0 INTRODUCTION

Based on the Ontario Hydro 1982 Grounding Guide/1/, surface grading material for transformer and switching stations should have a minimum thickness of 80 mm and an electrical resistivity comfortably greater than 3000 ohm-metres. Field testing performed by Ontario Hydro in 1960/2/, recommended that this grading material be a gravel having a minimum size of 6 mm. Ontario Hydro specifications issued in 1975 and 1983 /3/required the select grading material to be between 16 and 22 mm in size but allowed material as small as 9.5 mm to be accepted. Unfortunately, this narrow grain size material is not a standard product of Ontario aggregate producers and is becoming increasingly difficult to obtain. In addition, no standard test exists to determine the electrical resistivity of gravelly soils so that no performance measure existed for either the standardized fill material nor for any more commercially available aggregate that could be used in its place.

This report describes the development of an electrical resistivity test for surface grading material. The field conditions which the test method simulates, its limitations and its relation to tests proposed by others are described. Electrical resistivity measurements on surface fill from existing transformer stations, 19 mm coarse concrete aggregate, 19 mm HL8 asphalt aggregate, Granular A and Granular B are presented. The relative suitability of these materials as an electrical barrier in transformer stations and the factors affecting the materials' electrical resistivity are discussed.

2.0 FACTORS AFFECTING ELECTRICAL RESISTIVITY OF SOILS

The electrical resistance of crushed stone used as the surface insulating layer in transformer stations is not constant. The lowest resistivity occurs when the crushed stone is wet. Water films on the surface of the individual pieces of the crushed stone and fills the void spaces between particles, thereby forming the main conduction path for electric current. Conduction may also occur through the soil particles but this is considered minor unless the particles physically or chemically retain water (eg. clay or organic soil). Since the main conduction path is through the water, the conductivity of the water is very important.

Rainwater which may fall on a transformer station site during its operating life may have quite different conductivity from the tap water used to test surface fill materials in the laboratory. The size of the individual rock pieces and the degree of compaction of the rock pieces are also important. Larger pieces of crushed stone will have fewer contact points between a human foot print and an electrical ground point beneath the surface fill layer than smaller pieces of crushed stone. When the crushed stone is wetted there will be fewer continuous water films to provide an electrical path to a human foot if the rock has coarse particles than if the rock has smaller particles. Compaction densifies the crushed rock fill by rearranging the packing of the particles so that there are more particles per unit volume and more contact points. Therefore, a dense soil will have a lower resistivity than a loose soil having the same range of particle sizes. Fine grained soils or more compact soils are at a further disadvantage since their smaller intergranular spaces tend to restrict the flow of water slowing the rate of drainage and tending to keep resistivity low for a longer period after wetting.

In the winter, water in the surface soil turns to ice which is less conductive.

3.0 LABORATORY TEST METHODS

No standard laboratory test exists for measuring the electrical resistivity of coarse soils. For fine-grained soils such as sands, silts or clays, a standard ASTM test procedure does exist (ASTM-G57). This test procedure applies to at-grade or small sample measurements of soil resistivity using the Wenner four-electrode method. For small samples, a soil box, such as that manufactured by the M.C. Miller Co., is used to contain the soil during testing. The dimensions of the Miller soil box are 3.8 cm x 6.35 cm x 22.86 cm (1.5" x 2.5" x 9") which allows measurements of resistance in ohms to be directly converted to resistivity in ohm-cm. Unfortunately, these standard dimensions are too small to accommodate surface grading fill.

Coarse-grained materials have been tested by various agencies by constructing larger containers/4,5/. The key ingredients in these special tests are not the container dimensions, but the method of preparing the test soil, placing it in the test container and providing contact between the test soil and the electrical resistivity test circuit. Accompanying measurements of the soil grain size, soil density, water content and test water conductivity are also important. Most test methods reviewed tended to soak the subject soil and dump it into the test container, so that the tested soil was in a loose state. Generally, a flat metal plate, sometimes weighted down and sometimes underlain by aluminium foil, was used to provide electrical contact with the test soil. Containers up to 1 cubic foot were employed.

The test developed by Civil Research uses a 150 mm diameter PVC cylinder, 300 mm in height, to contain the test soil. Metal plates top and bottom provide electrical contact, assisted by a top weight and an upper and lower cushion layer of damp sand between the metal plates and the test soil (Figure 1). The purpose of the top weight is to ensure good contact between the top metal plate and the underlying sand layer. No attempt was made to simulate in-situ vertical loading. It was found that the thin layers of damp sand provide a more uniform contact area between the metal plates and the crushed stone. Electrical

resistivities obtained in this manner are lower than those obtained using flat end plate contacts alone. These resistivities are believed to be representative of the surface fill material but are conservative for worker safety because the worker boot contact area is similar to that of the flat plate. To further reproduce poor site conditions, the crushed stone samples are first submerged in tap water for several minutes, then loosely placed in the test apparatus for resistivity measurements. This procedure ensures that the surface of all particles are completely moistened prior to testing. In general, 80 to 100 mm (3 to 4 in) of sample is placed in the test cell to reproduce current station design criteria.

The measurement procedure first consists of using a variable autotransformer to produce a potential drop across the test cell. A high input impedance multimeter is placed in the circuit to measure the actual voltage drop. A second multimeter is placed in the circuit to measure the current flowing through the system. The calculated resistance is then converted to resistivity using the known dimensions of the crushed stone sample. Three tests are performed on the same sample by applying successively greater voltage drops and then determining the average resistivity. Sample density and moisture content are determined following each test.

For calibration purposes, a sand material was tested in both the ASTM standard apparatus and the Civil Research apparatus. Electrical resistivity measurements compared within a few percent, providing assurance that the new cell produces an acceptable measurement.

4.0 MATERIALS TESTED

The aim of this program was to compare the electrical resistivity properties of alternate fill materials with those of existing surface grading materials and with existing design specifications. To this end, two samples of surface materials were obtained from each of five existing transformer station sites. Two sources of coarse concrete aggregate and five sources of HL8 coarse asphalt aggregate were sampled. These materials had a maximum size of 19 mm. Two samples of Granular A and three samples of Granular B completed the test program. The grain size distribution curves for all samples tested, along with the material specifications, are provided in Appendix A.

The results of the testing program, including moisture contents, wet densities, uniformity coefficients (D_{60}/D_{10}) and electrical resistivities, are listed in Table I. As described in the previous section, the electrical resistivities were obtained on crushed stone samples which were surface wetted with tap water. No special effort was made to compact the samples to any particular density. The crushed stone was loosely placed in the test cell and only lightly packed to a total thickness of between 80 and 100 mm.

5.0 TEST RESULTS AND ANALYSIS

5.1 Existing TS Surface Grading Materials

Figure 2 is a summary grain size distribution plot of all samples collected from the following transformer stations: Cherrywood, Claireville, Manby, Milton and Strachan. These samples were collected from lightly travelled areas within each station. The Ontario Hydro specification for surface grading material is also plotted on Figure 2.

For the majority of samples tested, between 30% and 70% of the particles were smaller than the lower limit of the specification ie 16 mm. Approximately 10% of the particles were smaller than 9.5 mm. Eight of the ten samples had 2% or less of particles with diameters less than 5 mm. The electrical resistivities for the ten samples range from 4,300 to 10,300 ohm-m, under the conditions imposed by the test cell. Based on this small sample set, there does not appear to be any clear correlation between electrical resistivity and wet density or moisture content.

5.2 Alternate Surface Grading Materials

The gradation requirements for 19 mm structural concrete aggregate and HL8 are identical. From 100 to 90% of the particles must be less than 19 mm, 90 to 65% must be less than 16 mm, 55 to 20% must be less 9.5 mm and 10 to 0% may be less than 4.75 mm. The actual grain size distributions and gradation requirements for each sample of alternate material tested are provided in Appendix A. The gradations for five of the seven samples fall within the above requirements, while the gradations for two samples are actually coarser than the above requirements. Tests on seven of the alternate materials yielded electrical resistivity values ranging from approximately 1,800 to 13,800 ohm-m, with five of the seven exceeding 4,000 ohm-m. Once again, based on this small sampling, there does not appear to be any correlation between electrical resistivity and sample wet density or moisture content.

In contrast to the coarse aggregate materials tested above, the Granular A and Granular B materials yielded dramatically different electrical resistivities. As shown in Table I, all of the samples yielded values at or less than 1,000 ohm-m. These low values are probably due to the abundance of finer particles which lead to a greater number of wetted contact points. The higher wet densities and moisture contents exhibited by these samples confirm this hypothesis.

5.3 Estimating Lower Bound of Electrical Resistivity

Figures 3 and 4 are plots of electrical resistivities of samples tested versus wet density and versus degree of saturation respectively. No consistent relationship appears to exist in either of these plots, especially when resistivities are high ie > 4,000 ohm-m. However, it is apparent that the electrical resistivity of a sample is greater than 3,000 ohm-m when its wet density is less than 1,600 kg/m^3 or when the degree of saturation is less than 10%. If

additional data confirm the above observations, a useful procedure may be developed for initial screening of potential surface grading materials.

6.0 SUMMARY AND RECOMMENDATIONS

1. A test cell has been developed and a testing methodology outlined for measuring the electrical resistivity of crushed stone with particle sizes up to 22.5 mm in diameter.

2. Samples of surface grading material from five transformer stations in the vicinity of Metropolitan Toronto were obtained and tested for grain size distribution and electrical resistivity. All samples had resistivities greater than 3,000 ohm-m, even though from 30 to 70% of the particle sizes were less than 16 mm in diameter and therefore out of specification.

3. Seven samples of 19 mm structural concrete aggregate and 19 mm asphalt aggregate (HL8) were obtained from several sources. Five of the seven samples tested had resistivities greater than 4,000 ohm-m. These initial results are encouraging and indicate that these two materials could potentially be used as alternates for surface grading at transformer stations. Since a relatively small number of samples were tested and two of the seven samples had resistivities less than 3,000 ohm-m, a stringent testing program would have to be implemented and approval obtained prior to the use of any alternate materials.

4. It is very important to note the conditions imposed on the crushed stone samples by the testing methodology. All samples were tested surface wet only. This implies that if any water were to accumulate within the crushed stone layer in the field, the laboratory electrical resistivity values would be invalid. Because of this aspect alone, proper drainage of transformer station yards must be included as an important component of worker safety.

5. All samples were tested with tap water which had an electrical conductivity of approximately 400 micro Siemens/cm and a neutral pH. The effect of acid rain on the electrical resistivity of crushed stone, especially from a limestone parent material, has not been determined.

6. All samples were tested in a relatively loose state. A couple of tests conducted on moderately compacted and dense samples of alternate surface grading materials, yielded resistivities below 1,000 ohm-m for a soil which had tested at 4,800 ohm-m in the loose state. This result is probably due to an increased number of particle contact points and to some grain crushing caused by the compaction process.

Based on the test results obtained during this program, the following recommendations are made:

1. For surface grading of transformer station yards, 19 mm coarse concrete aggregate or 19 mm coarse asphalt aggregate can be used as alternate materials. Acceptance tests must be made of prospective supply sources to confirm the 3,000 ohm-m criteria, since testing to date has shown that some 19 mm materials are not electrically suitable. The suitability of these alternate materials for use as structural fills or as load-carrying surfaces has not been investigated in this program.

2. The laboratory test program should be continued to further investigate the effects of sample density, water conductivity, degree of saturation and rate of drainage, on the electrical resistivity of crushed stone. Synthetic samples could also be made and tested to help clarify the importance of fines content on electrical resistivity.

3. A long-term program should be initiated to obtain additional samples of surface grading materials from existing transformer stations and from sources of alternate materials. This program should aim to collect a statistically significant number of electrical resistivity test results, so that average values and confidence intervals may be determined for specific sources of materials. This more comprehensive program is necessary for establishing new surface grading material specifications for Ontario Hydro design standards and practices.

Approved by:

J.B. Brown
Manager
Civil Research Department

Prepared by

C.B.H. Cragg
Senior Engineer
Soil Sciences Section

A.G. Vorauer
Engineer
Soil Sciences Section

Reviewed by:

T.J. Carmichael
Supervising Engineer
Soil Sciences Section

CBHC/AGV:LM

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1. Ontario Hydro Grounding Guide, 1982 edition.

2. Eleck, A. Variations of Foot-Resistance on Crushed Stone, Ontario Hydro Research Report No 60-404, December, 1960.

3. Ontario Hydro Design Standards and Practices, Transformer and Switching Station Finish Grading, No. 12220-001 R2, March, 1975.

4. Barbeito, F. Substation Ground Grid Tests - Florida Power Corporation, Southeastern Electric Exchange Engineering and Operations Conference, Bal Harbour, Florida, June 1-3, 1988.

5) Abledu, K.O. and Laird, D.N. Measurement of Substation Rock Resistivity. IEEE/PES 1991 Winter Meeting, New York, NY, February 3-7, 1991.

CLASSIFICATION	SOURCE		PETRO. DATA	PARTICLE SIZE ANALYSIS	D_{60}/D_{10}	M/C (%)	WET DENSITY (kg/m)	ELECTRICAL RESISTIVITY (ohm-m)
EXISTING T. S. SURFACE FILL	CHERRYWOOD	S - 1		✔	1.7	0.9	1520	7333
		S - 2		✔	1.7	1.2	1479	4905
	CLAIREVILLE	S - 1		✔	1.7	2.1	1471	6057
		S - 2		✔	1.7	1.7	1468	8387
	MANBY	S - 1		✔	1.8	3.2	1560	4272
		S - 2		✔	2.0	1.9	1554	10261
	MILTON	S - 1		✔	2.3	2.5	1490	5138
		S - 2		✔	2.4	3.8	1438	6845
	STRACHAN	S - 1		✔	1.8	2.3	1391	5424
		S - 2		✔	1.8	3.0	1438	4707
3/4" COARSE STRUCTURAL CONCRETE AGG.	DUFFERIN - MILTON		✔	✔	2.1	3.1	1543	4779
	E. C. KING - TARA , OWEN SOUND		✔	✔	1.3	3.4	1637	6802
HL8 COARSE AGG. (3/4" AGG. WASHED)	TESKEY - MILTON		✔	✔	2.1	2.4	1590	4006
	STD. AGG. - HAGERSVILLE		✔	✔	2.1	3.8	1618	1779
	OXFORD SAND & GRAVEL - WOODSTOCK		✔	✔	2.4	2.5	1663	2797
	PIONEER CONSTR. - SUDBURY		✔	✔	2.0	2.3	1496	4552
	TRENT VALLEY - NORFOLK			✔	1.9	2.2	1425	13818
GRANULAR "A"	JAMES DICK CONSTR. - BOLTON			✔	47	10.1	1841	1043
	DUFFERIN - MILTON		✔	✔	48	7.6	1991	532
GRANULAR "B"	JAMES DICK CONSTR. - BOLTON			✔	145	8.5	2591	832
	FRANCESCHINI AGG. - BRAMPTON		✔	✔	76	7.6	2266	514
	DUFFERIN - MILTON		✔	✔	48	6.2	1883	484

TABLE 1

ELECTRICAL RESISTIVITY - T. S. SURFACE STONE

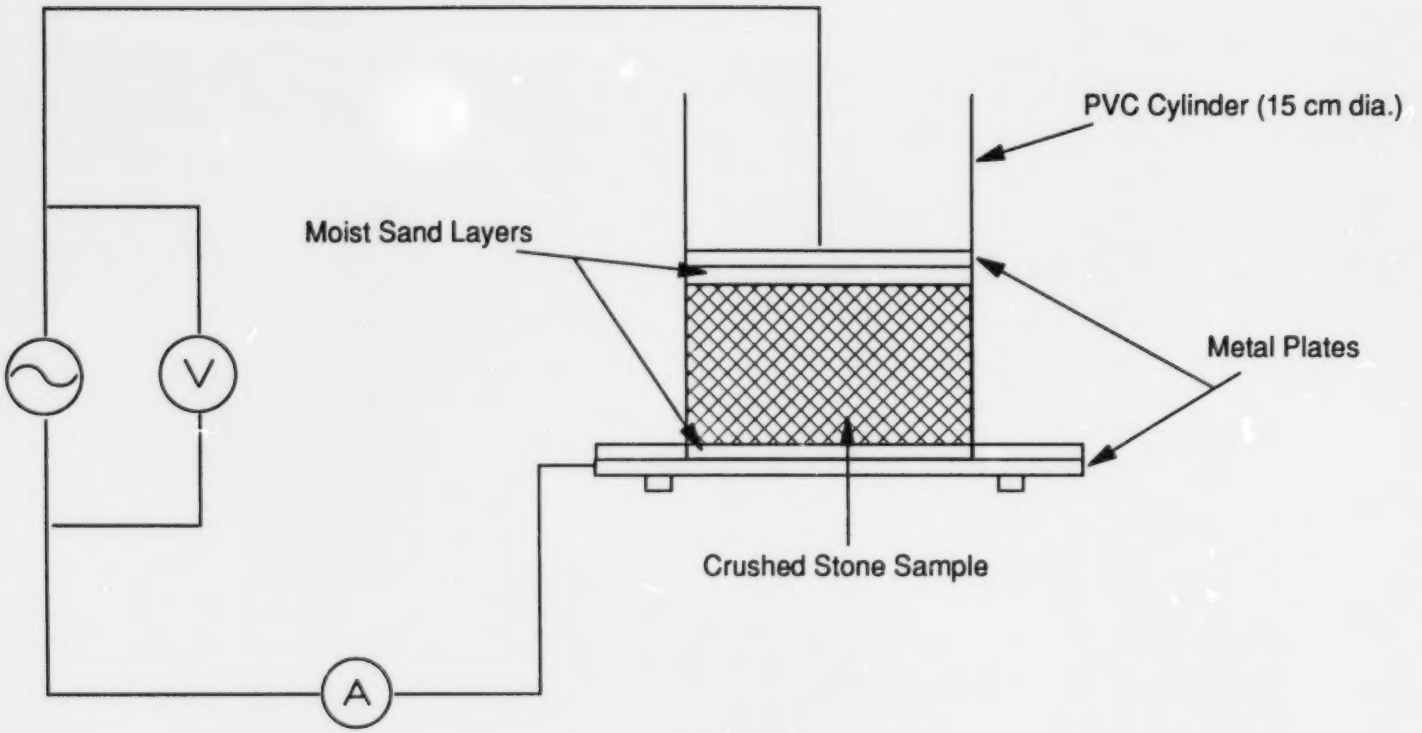

Figure 1
Schematic of Electrical Resistivity Test Set-Up

MECHANICAL ANALYSIS – TRANSFORMER STATION SURFACE STONE

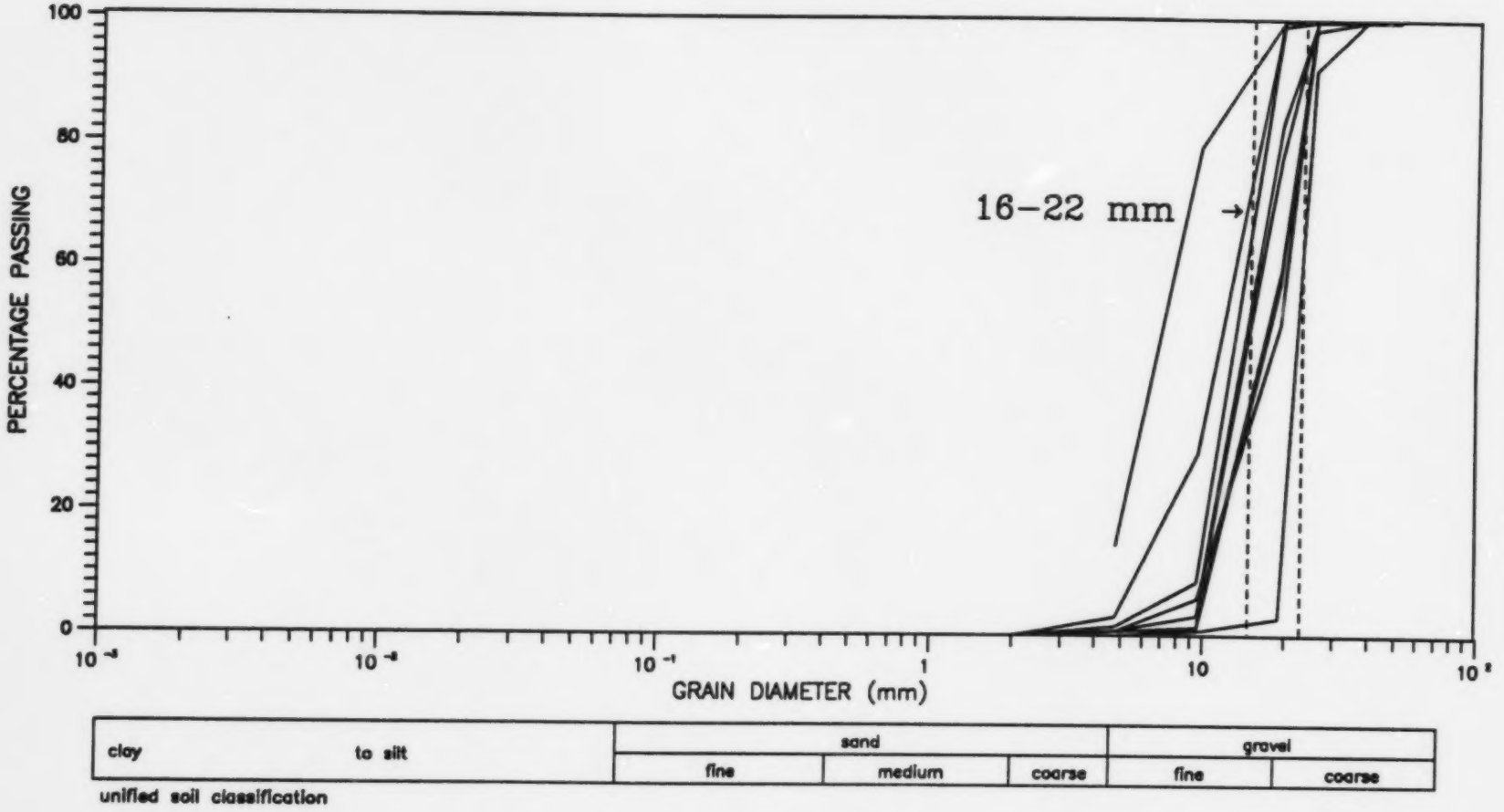

Figure 2

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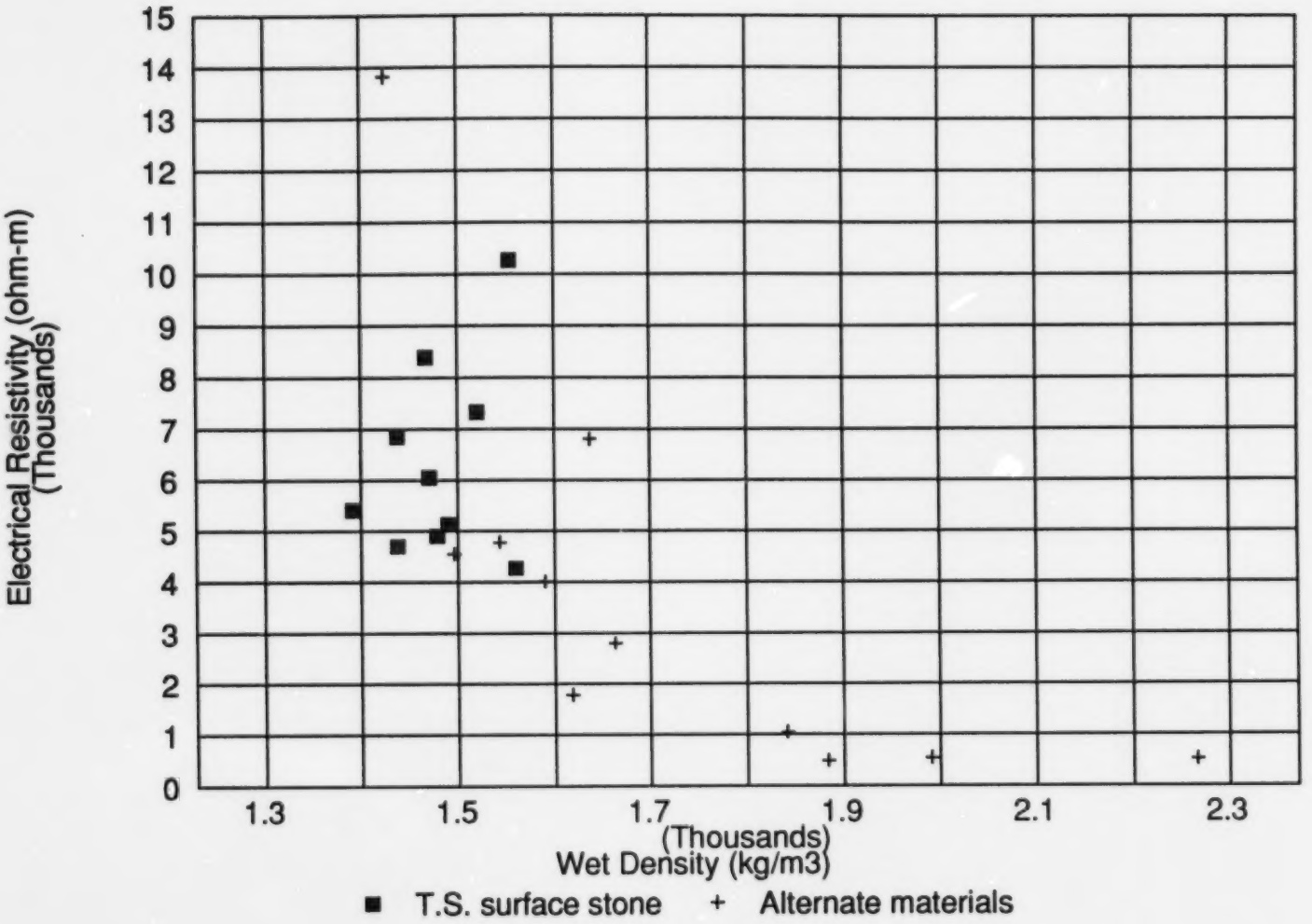


Figure 3
Electrical Resistivity of Crushed Stone vs. Wet Density

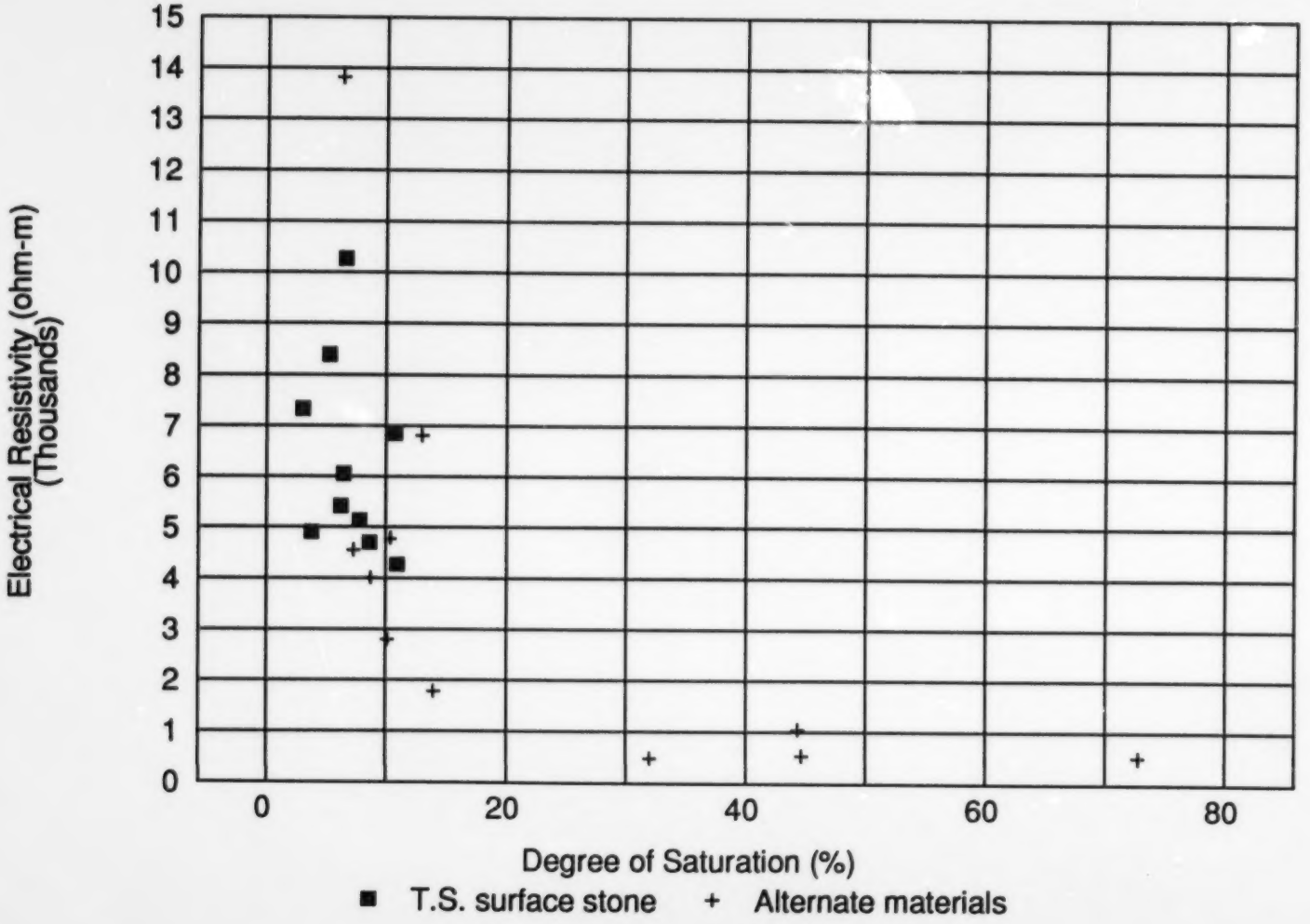
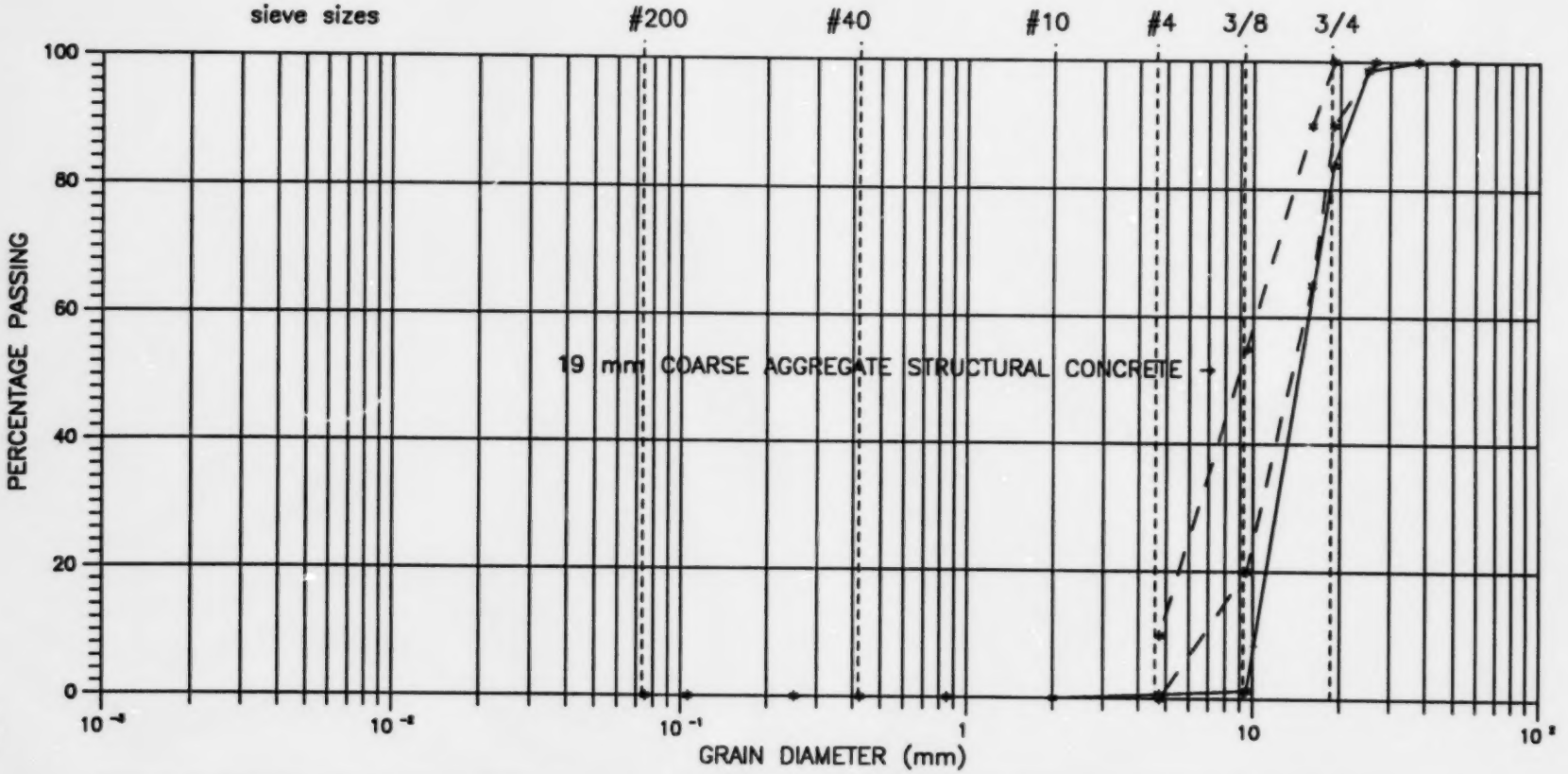


Figure 4
Electrical Resistivity of Crushed Stone vs. Degree of Saturation

APPENDIX A

Grain Size Distribution Curves

MECHANICAL ANALYSIS – CHERRYWOOD T. S. SURFACE STONE – SAMPLE 1



clay	to silt	sand			gravel	
		fine	medium	coarse	fine	coarse

unified soil classification

◆◆◆◆ ELECTRICAL RESISTIVITY = 7333 ohm-m

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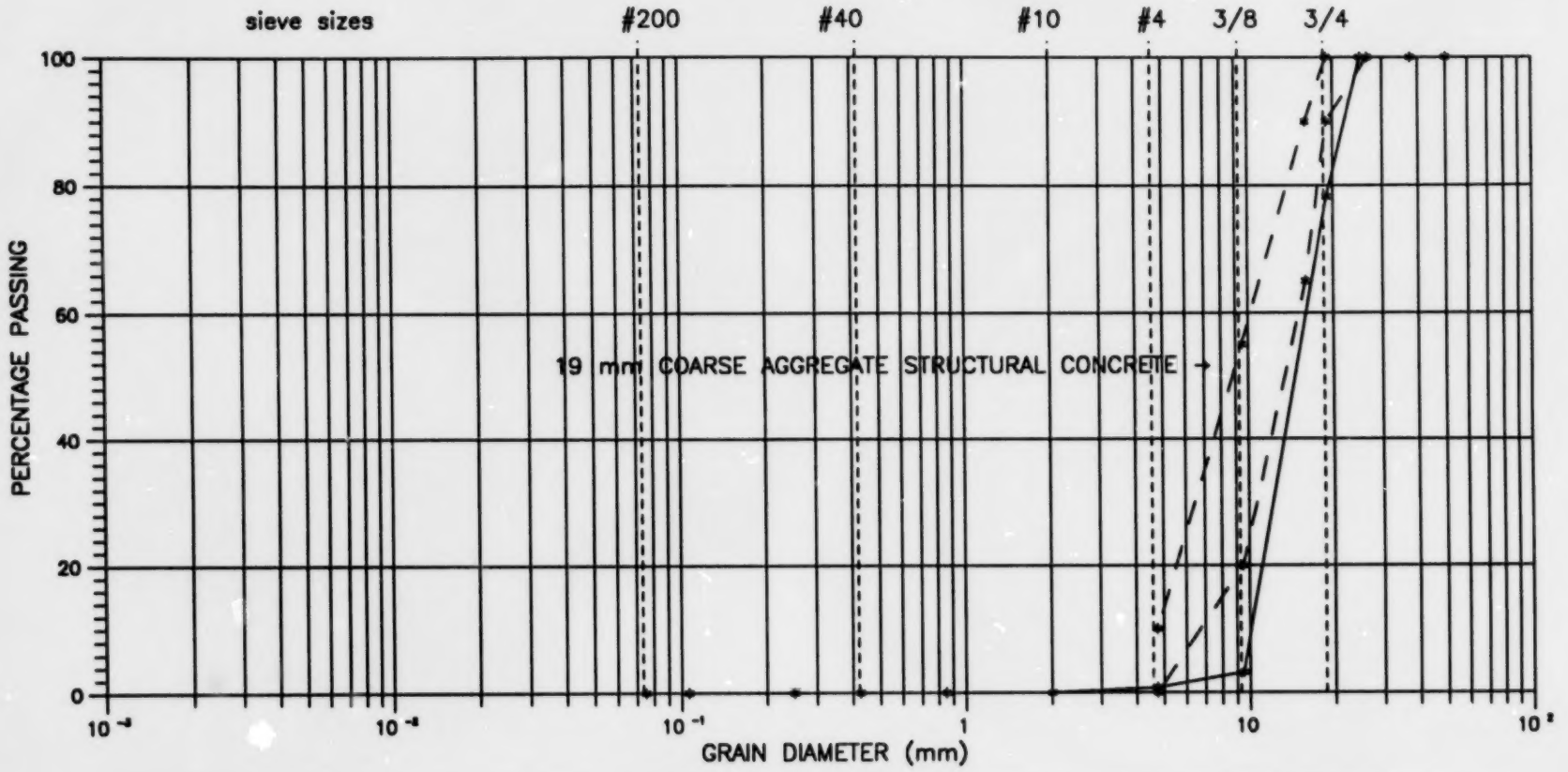
MECHANICAL ANALYSIS – CHERRYWOOD T. S. SURFACE STONE – SAMPLE 2



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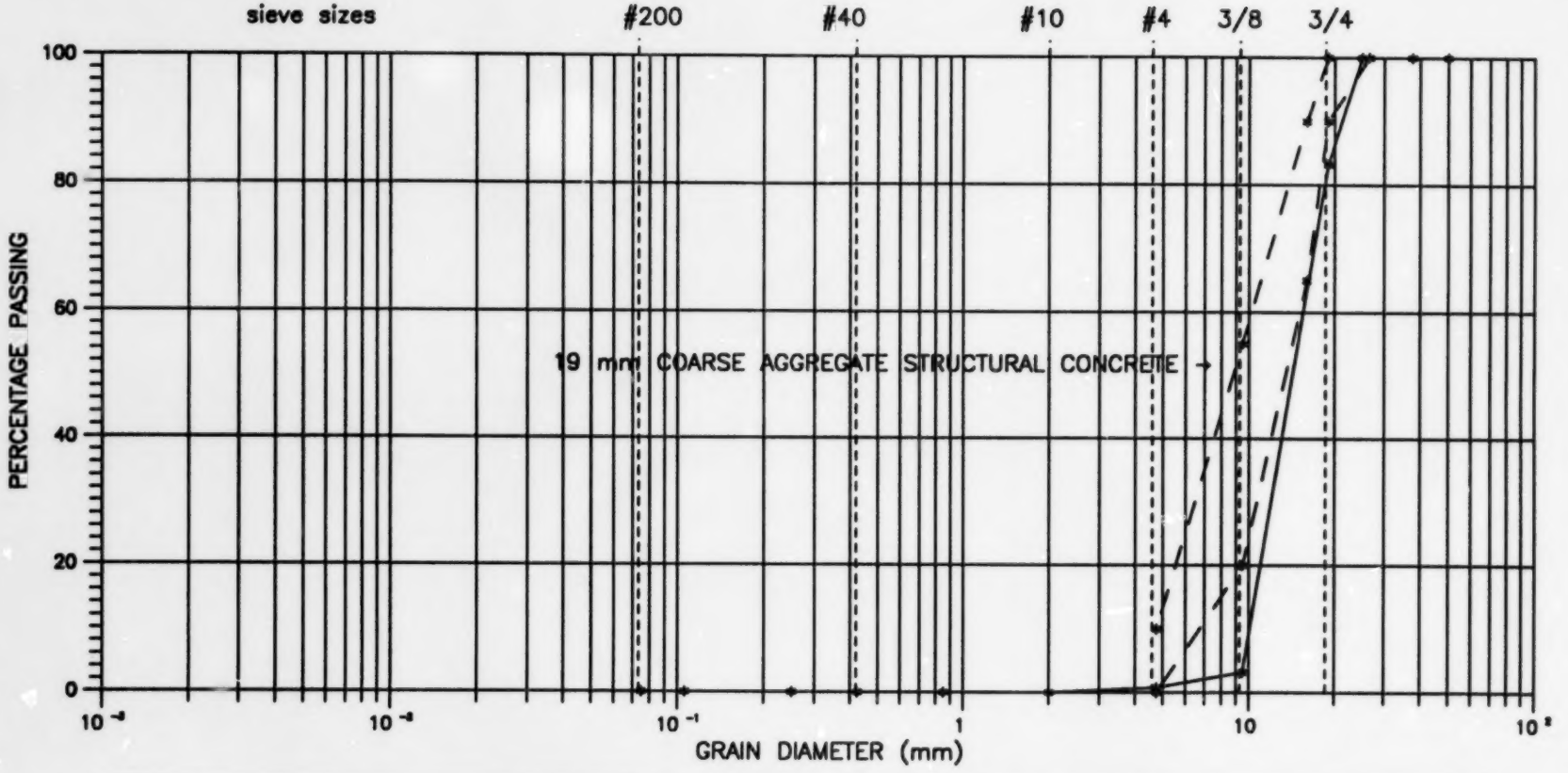
MECHANICAL ANALYSIS – CLAIRVILLE T. S. SURFACE STONE – SAMPLE 1



clay	to silt	sand			gravel	
		fine	medium	coarse	fine	coarse

unified soil classification

◆◆◆◆ ELECTRICAL RESISTIVITY = 6057 ohm–m

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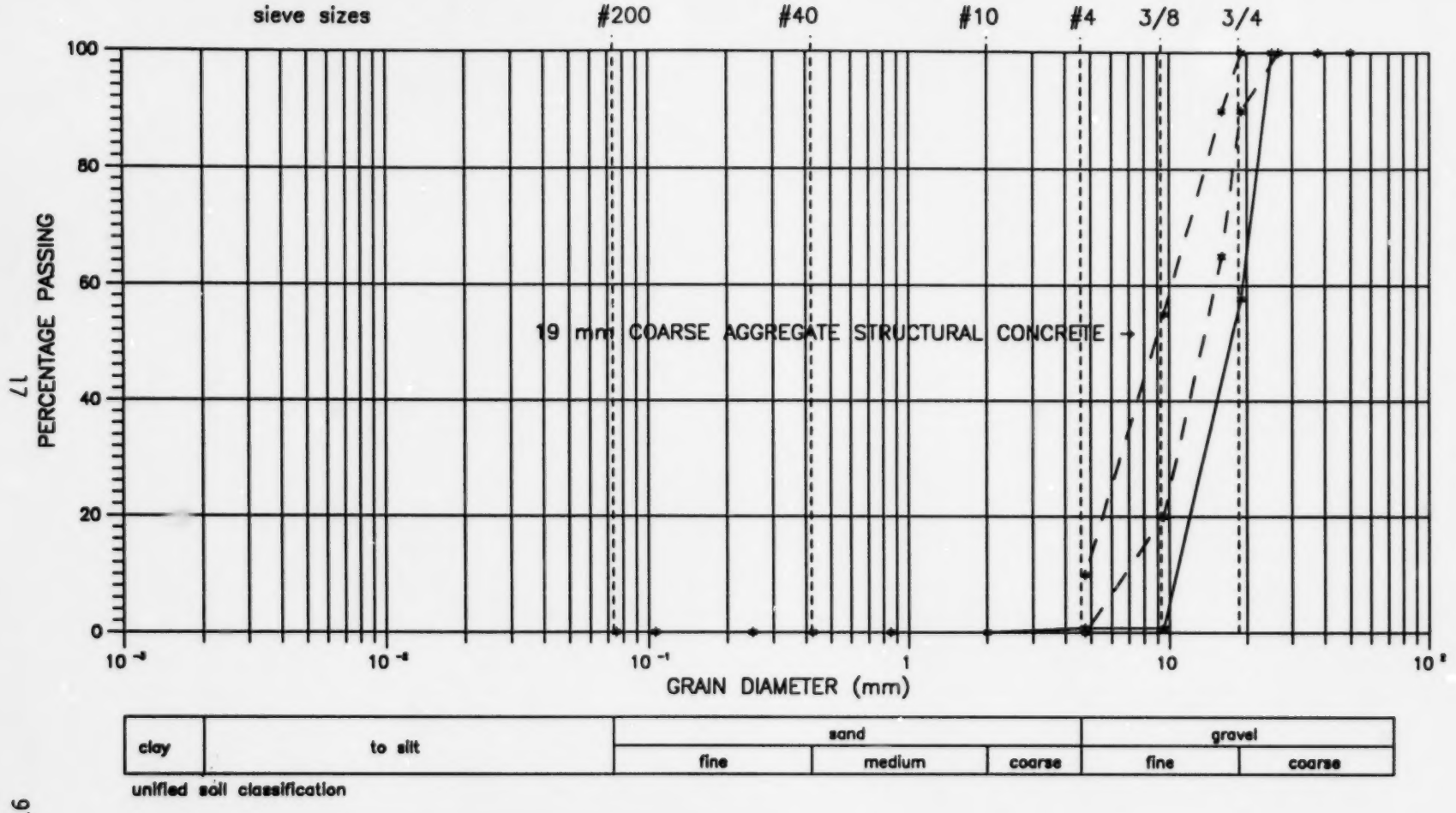
MECHANICAL ANALYSIS – CLAIRVILLE T. S. SURFACE STONE – SAMPLE 2



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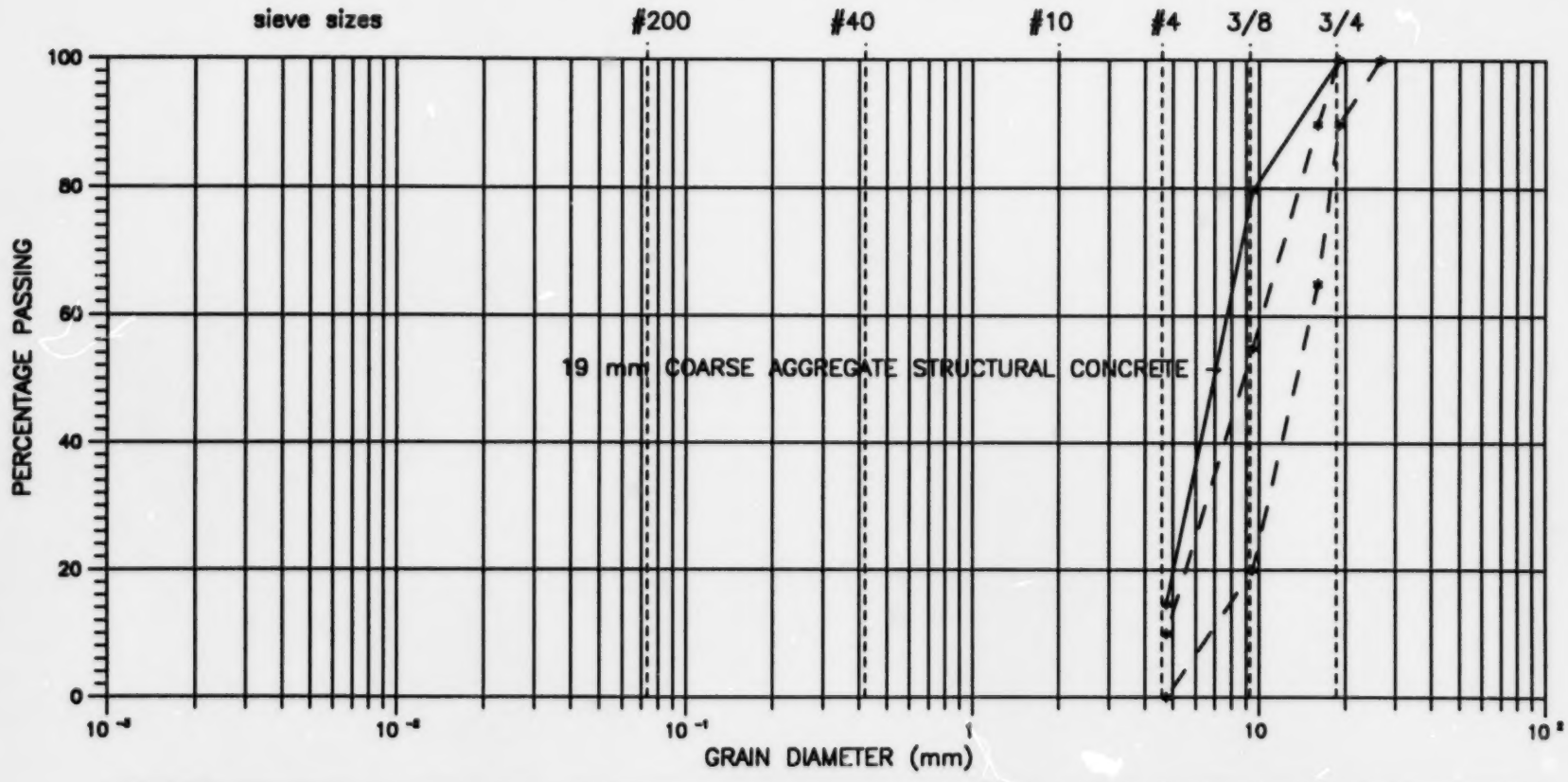
MECHANICAL ANALYSIS – MANBY T. S. SURFACE STONE – SAMPLE 1



clay	to silt	sand			gravel	
		fine	medium	coarse	fine	coarse

unified soil classification

ELECTRICAL RESISTIVITY = 4272 ohm–m

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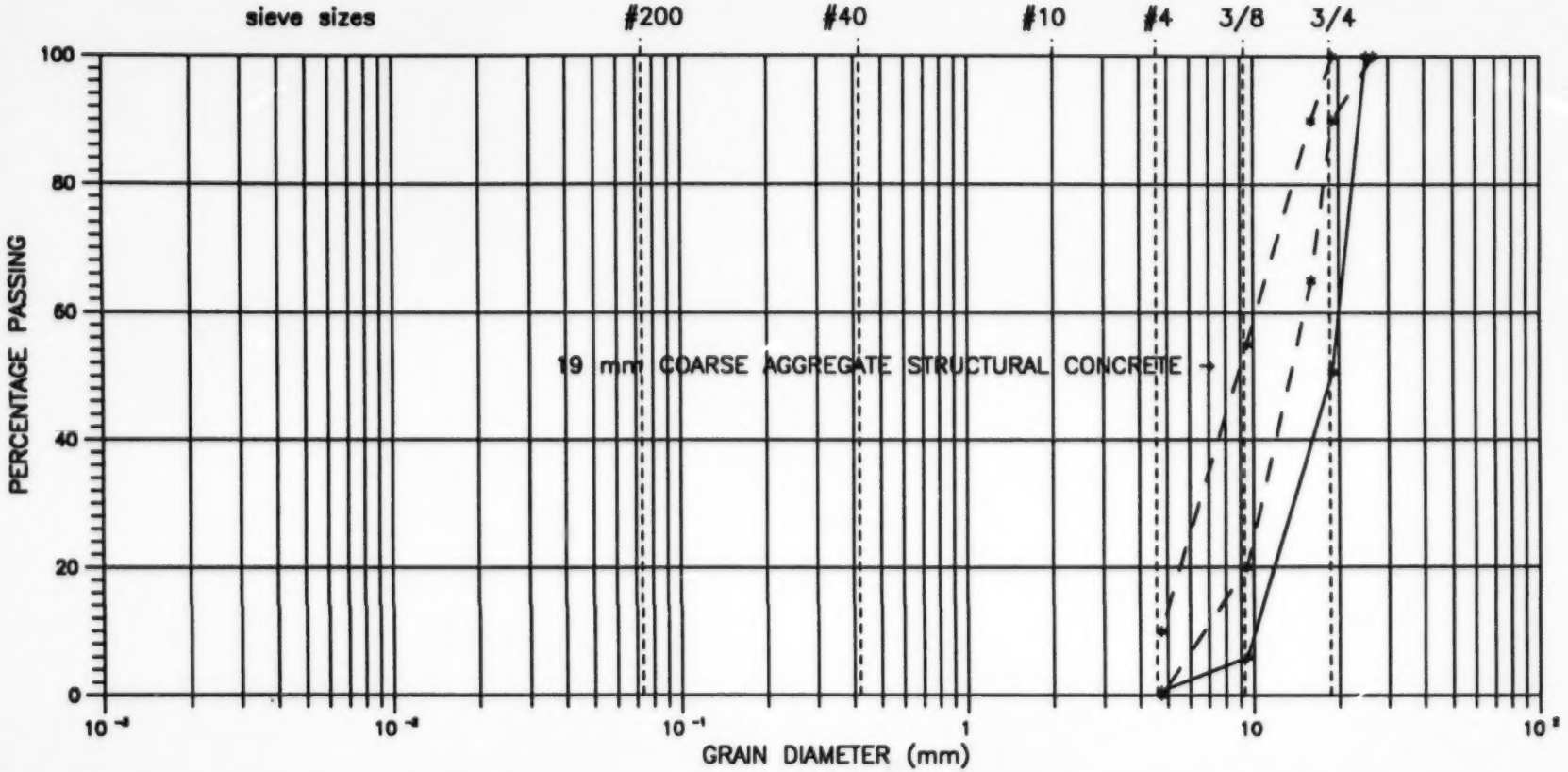
MECHANICAL ANALYSIS – MANBY T. S. SURFACE STONE – SAMPLE 2



clay	to silt	sand			gravel	
		fine	medium	coarse	fine	coarse

unified soil classification

◆◆◆◆◆ ELECTRICAL RESISTIVITY = 10261 ohm–m

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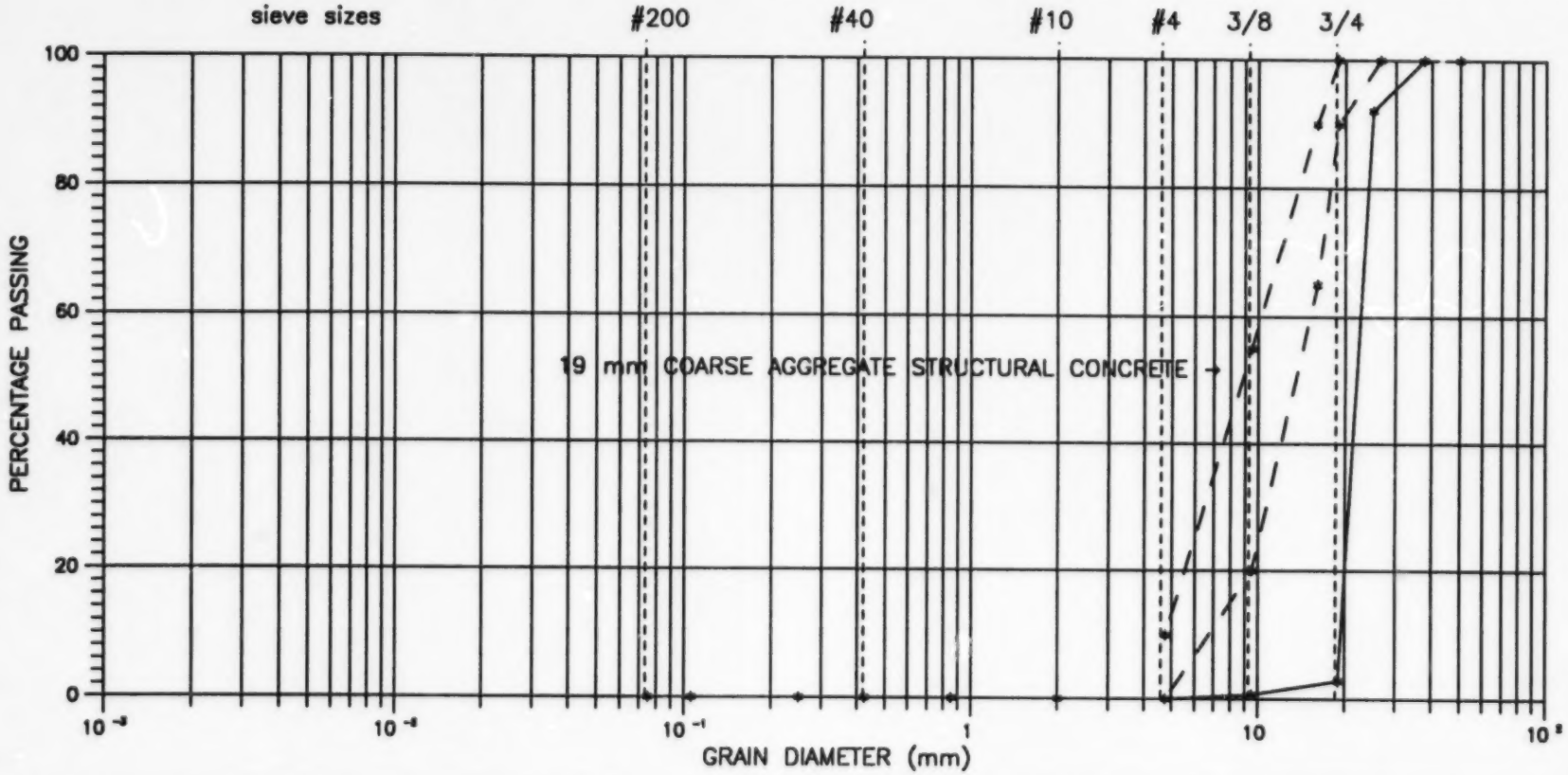
MECHANICAL ANALYSIS – MILTON T. S. SURFACE STONE – SAMPLE 1



clay	to silt	sand			gravel	
		fine	medium	coarse	fine	coarse

unified soil classification

◆◆◆◆◆ ELECTRICAL RESISTIVITY = 5138 ohm-m

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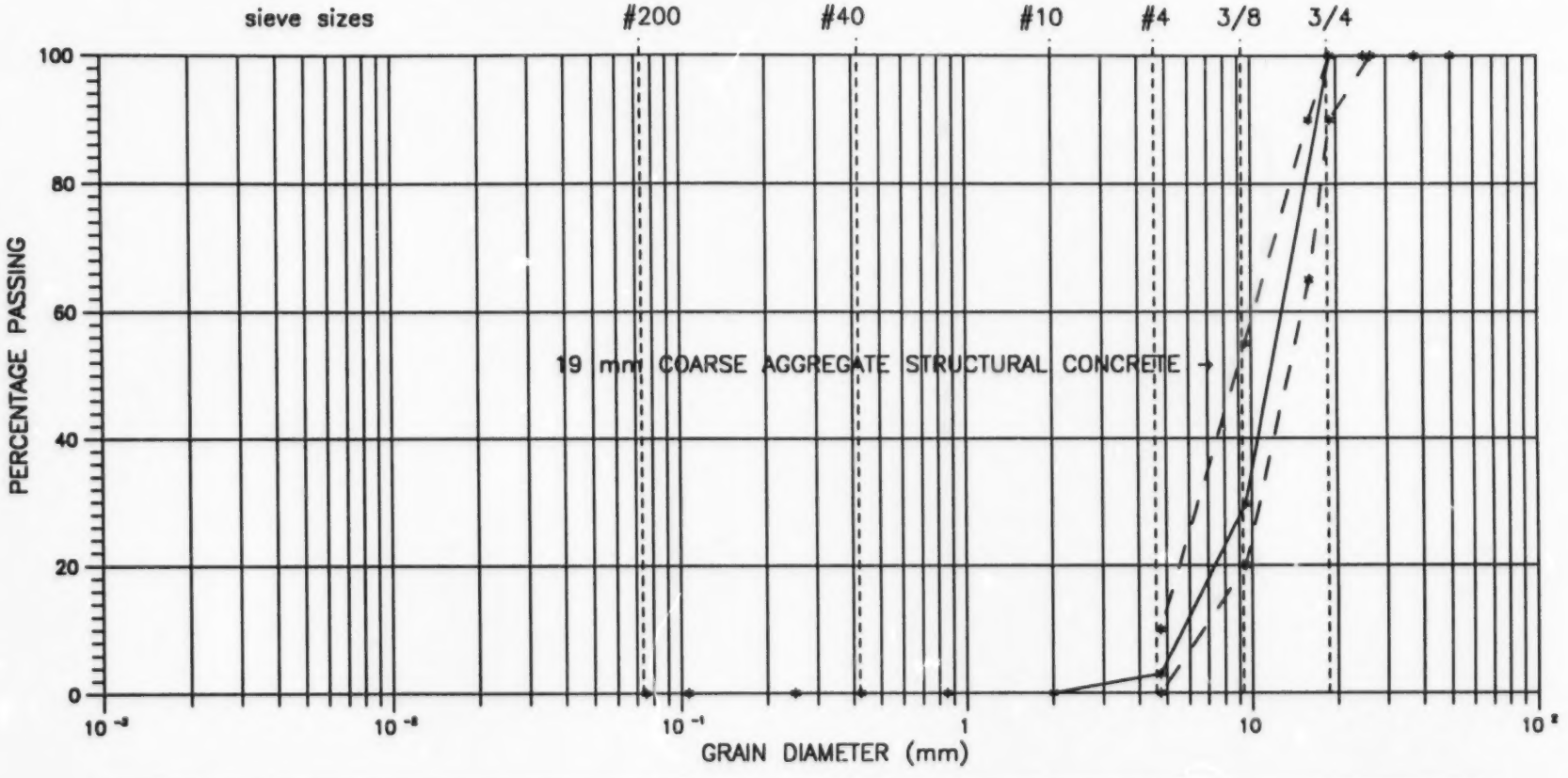
MECHANICAL ANALYSIS – MILTON T. S. SURFACE STONE – SAMPLE 2



clay	to silt	sand			gravel	
		fine	medium	coarse	fine	coarse

unified soil classification

★★★★★ ELECTRICAL RESISTIVITY = 6845 ohm-m

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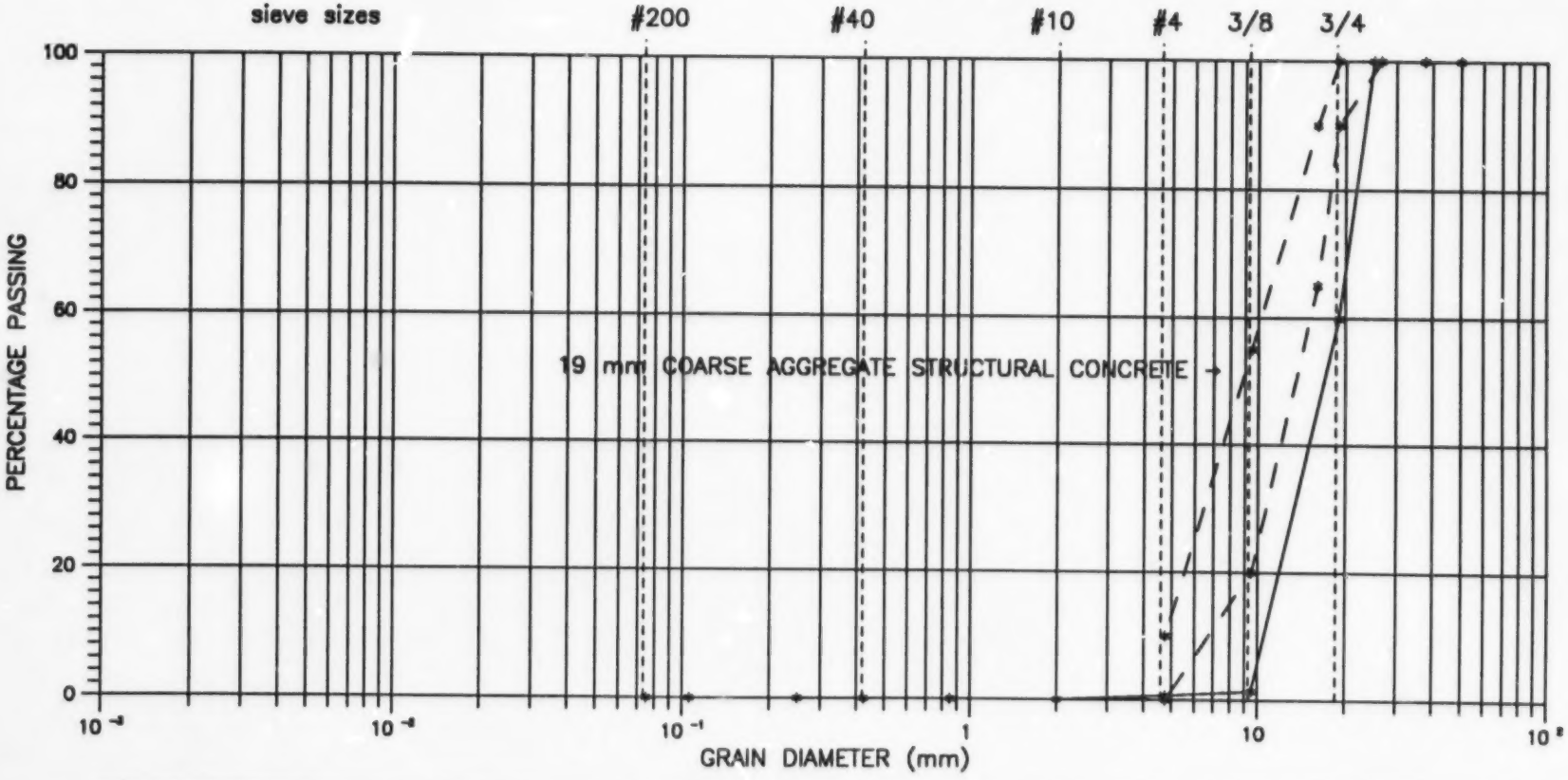
MECHANICAL ANALYSIS – STRACHEN T. S. SURFACE STONE – SAMPLE 1



clay	to silt	sand			gravel	
		fine	medium	coarse	fine	coarse

unified soil classification

◆◆◆◆◆ ELECTRICAL RESISTIVITY = 5424 ohm-m

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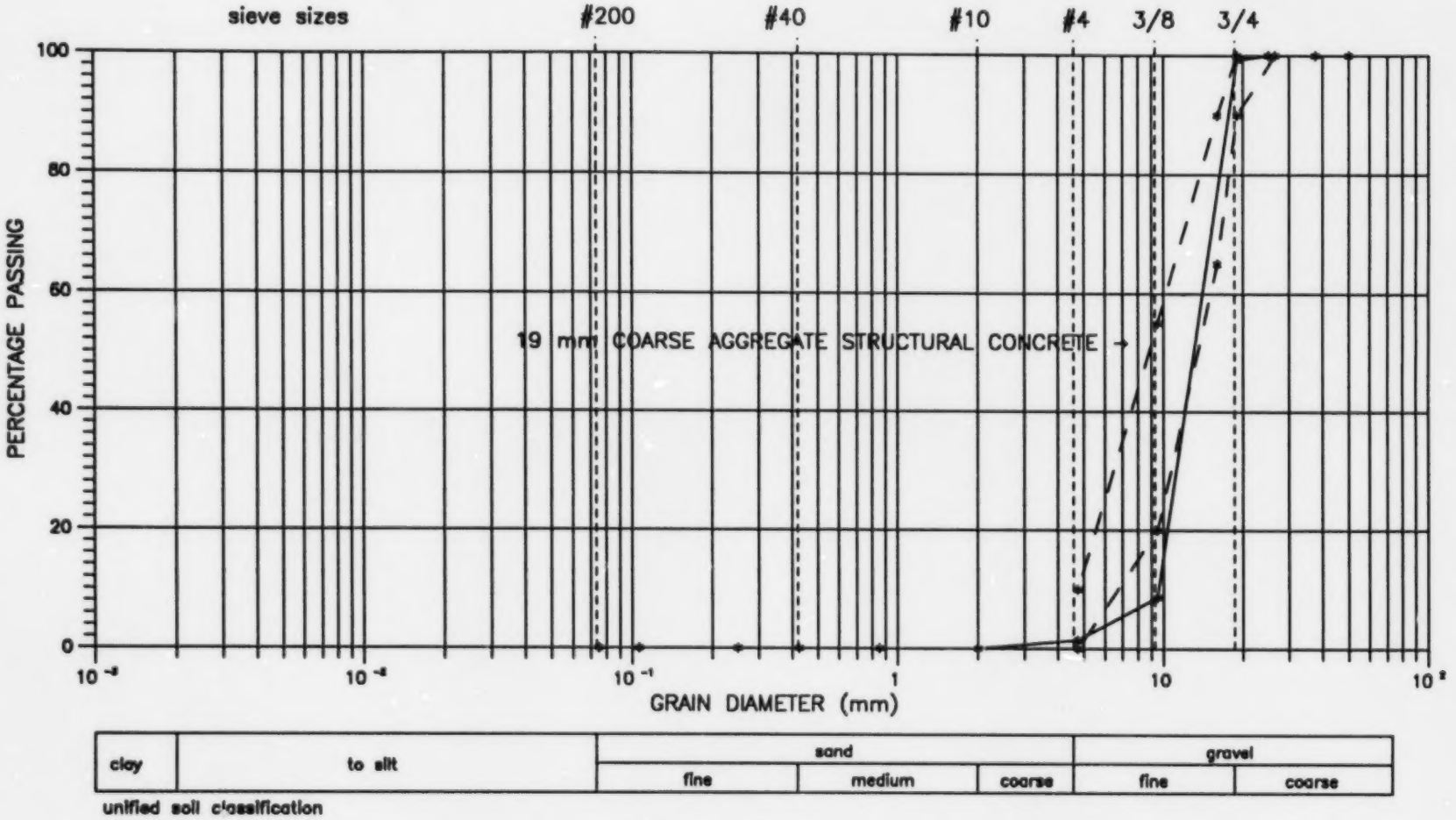
MECHANICAL ANALYSIS – STRACHEN T. S. SURFACE STONE – SAMPLE 2



●●●●● ELECTRICAL RESISTIVITY = 4707 ohm-m

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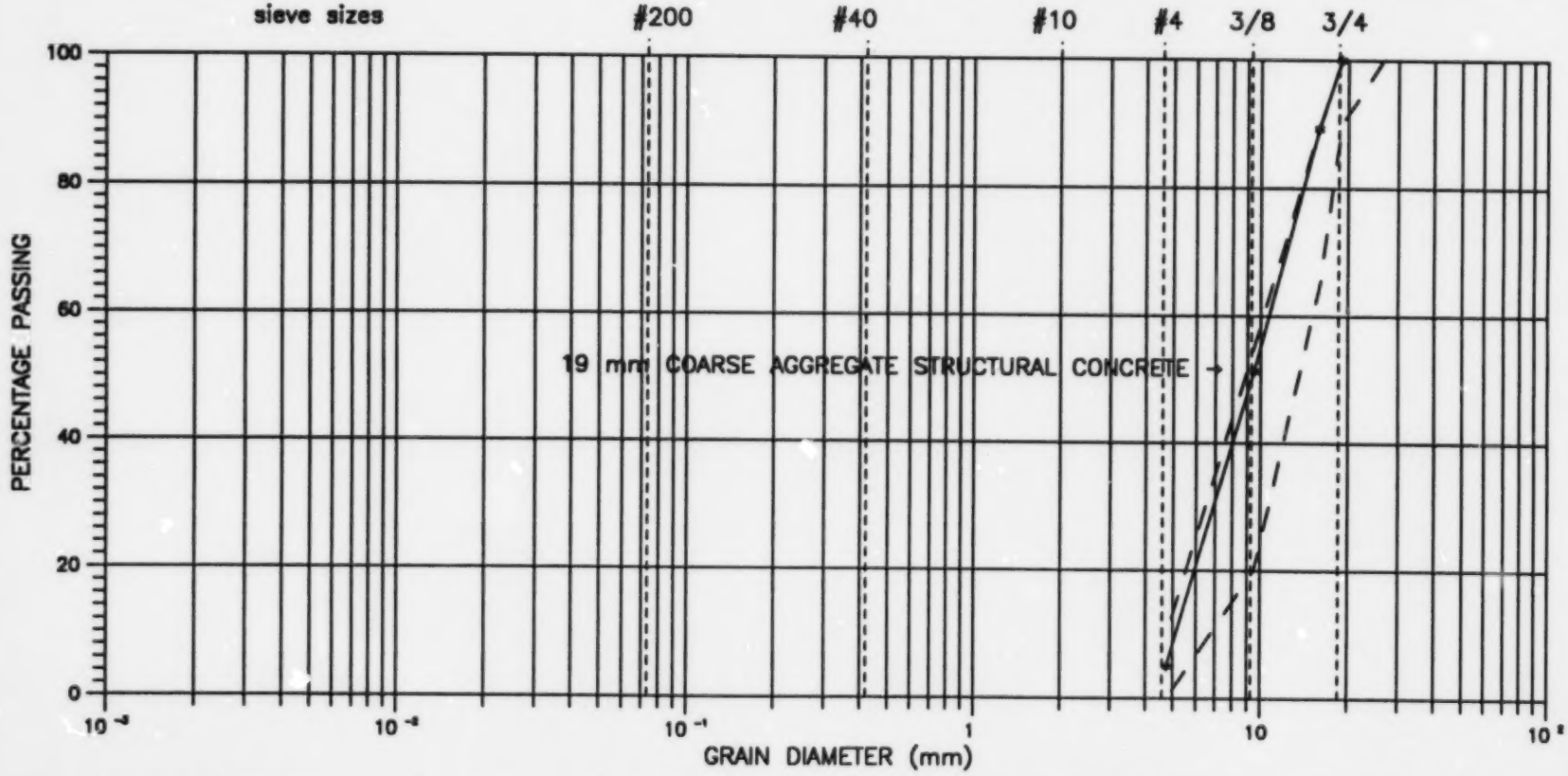
MECHANICAL ANALYSIS – MILTON QUARRY – 19 mm STRUCTURAL CONCRETE AGG.



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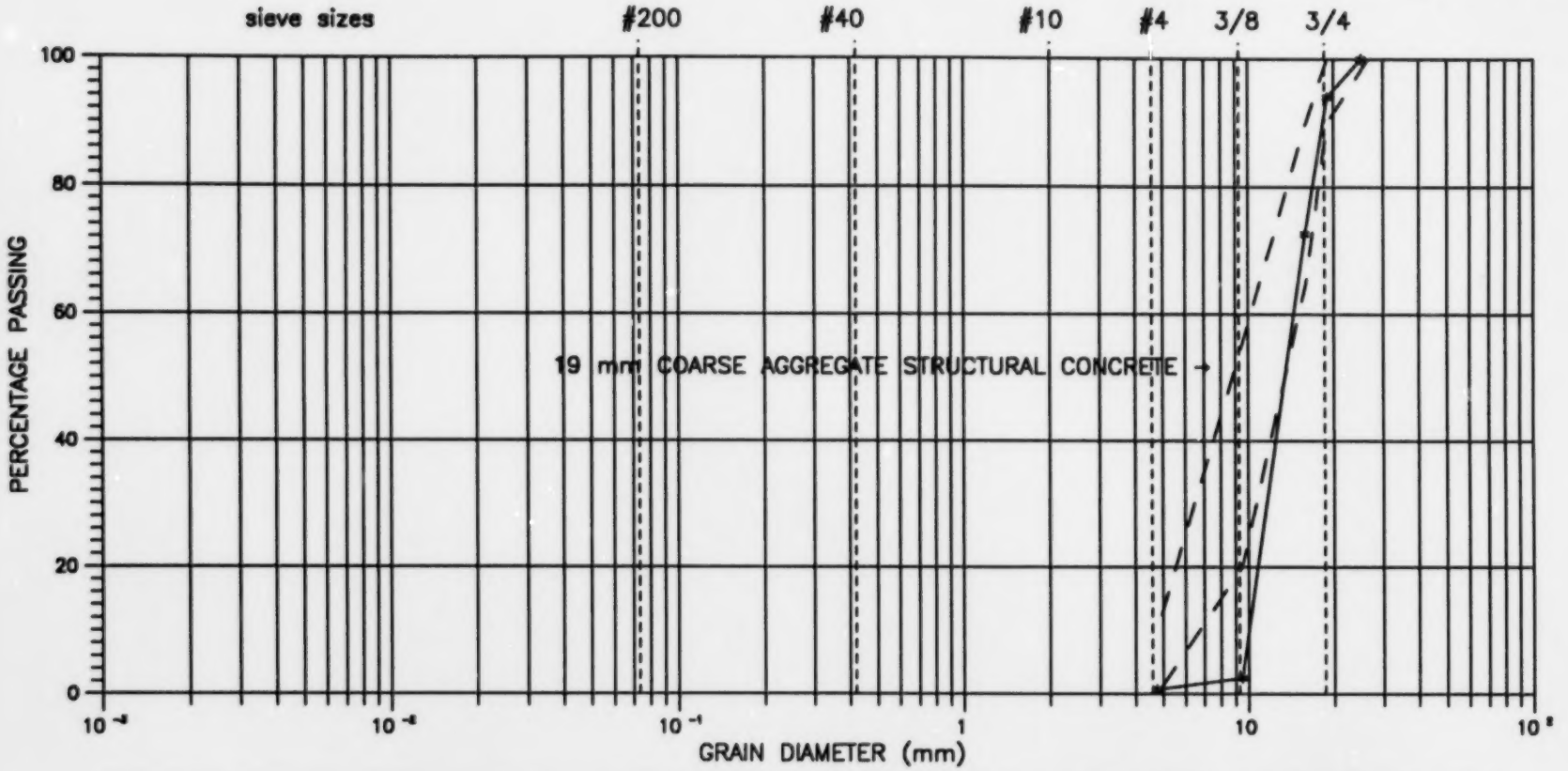
MECHANICAL ANALYSIS – TARA PIT – 19 mm STRUCTURAL CONCRETE AGG.



clay	to silt	sand			gravel	
		fine	medium	coarse	fine	coarse

unified soil classification

◆◆◆◆◆ ELECTRICAL RESISTIVITY = 6802 ohm-m

ONTARIO HYDRO
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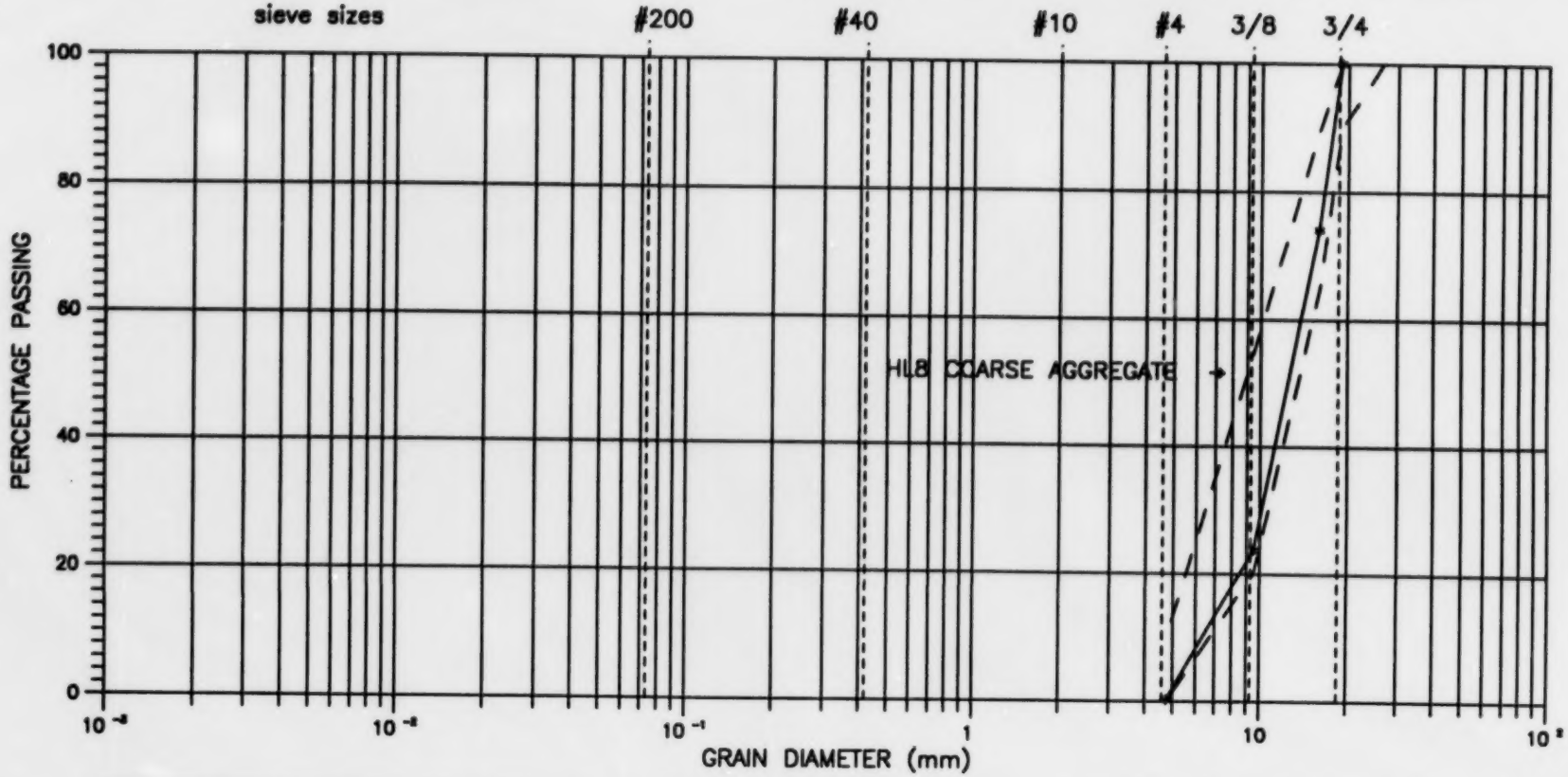
MECHANICAL ANALYSIS – MILTON QUARRY – HL8 COARSE AGGREGATE



clay	to silt	sand			gravel	
		fine	medium	coarse	fine	coarse

unified soil classification

◆◆◆◆◆ ELECTRICAL RESISTIVITY = 4006 ohm–m

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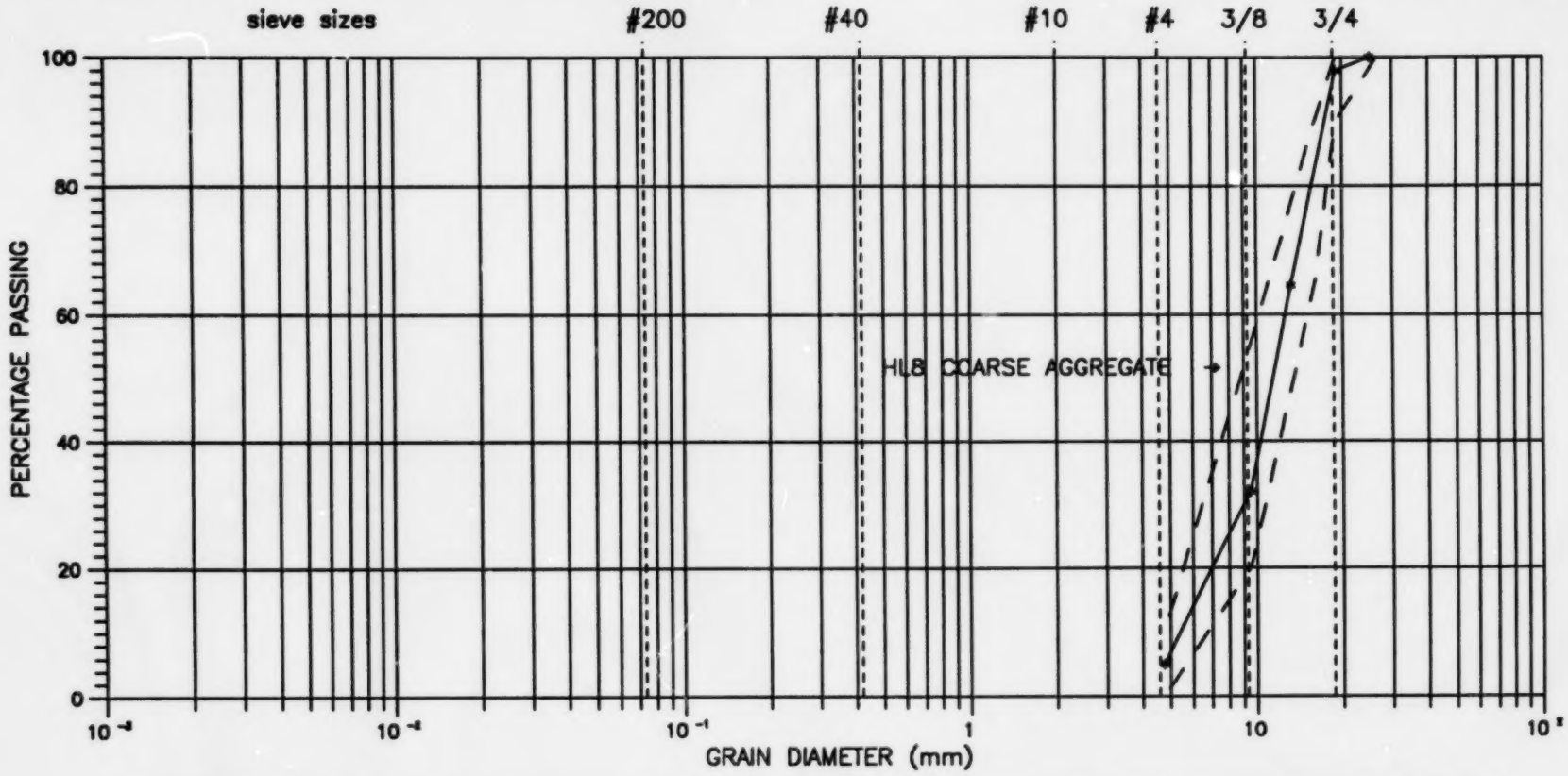
RESEARCH DIVISION

MECHANICAL ANALYSIS – STANDARD AGG. HAGERSVILLE – HL8 COARSE AGGREGATE



clay	to silt	sand			gravel	
		fine	medium	coarse	fine	coarse

unified soil classification

●●●●● ELECTRICAL RESISTIVITY = 1779 ohm–m

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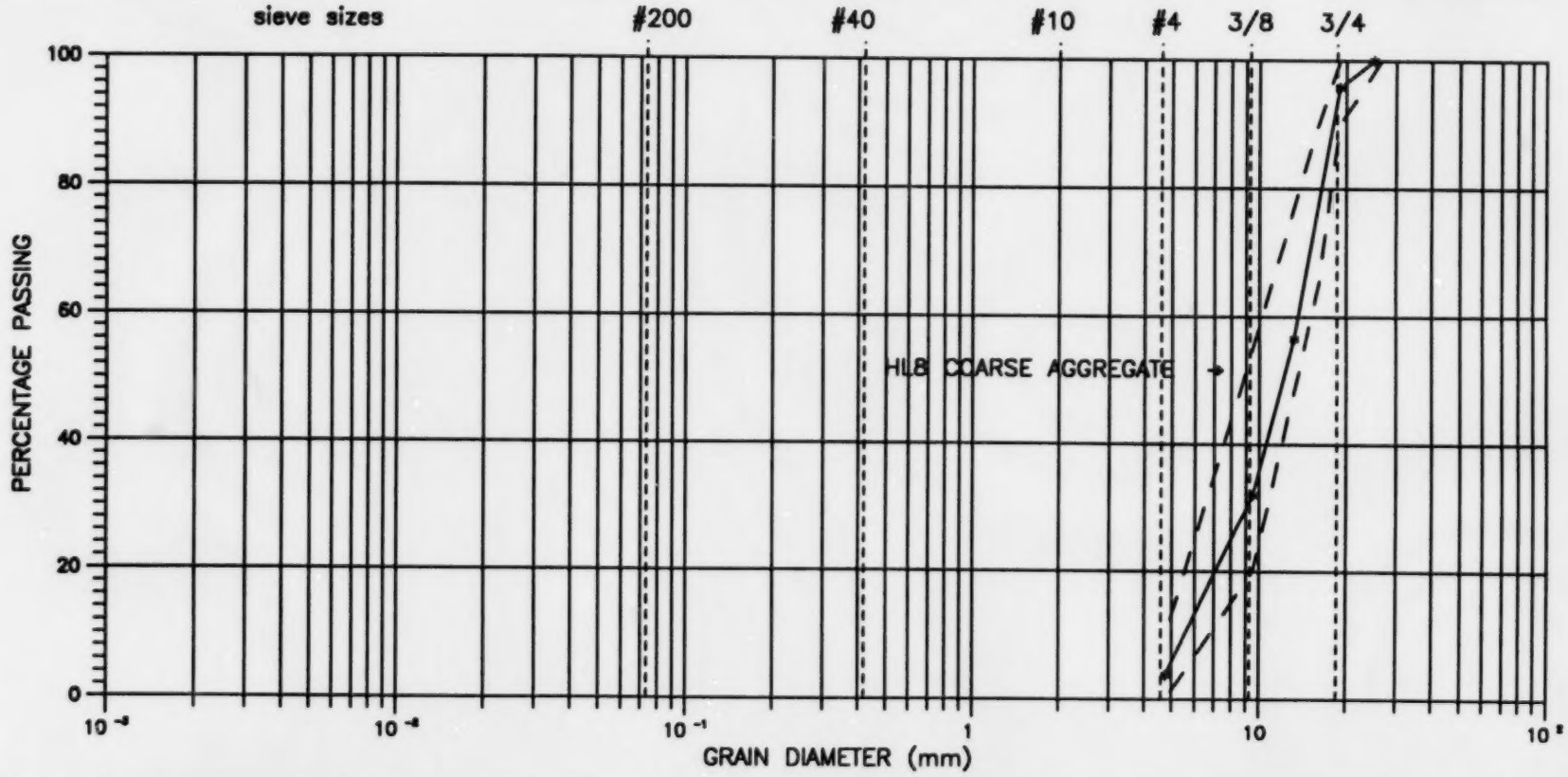
MECHANICAL ANALYSIS – OXFORD SAND AND GRAVEL – HL8 COARSE AGGREGA



clay	to silt	sand			gravel	
		fine	medium	coarse	fine	coarse

unified soil classification

◆◆◆◆◆ ELECTRICAL RESISTIVITY = 2797 ohm–m

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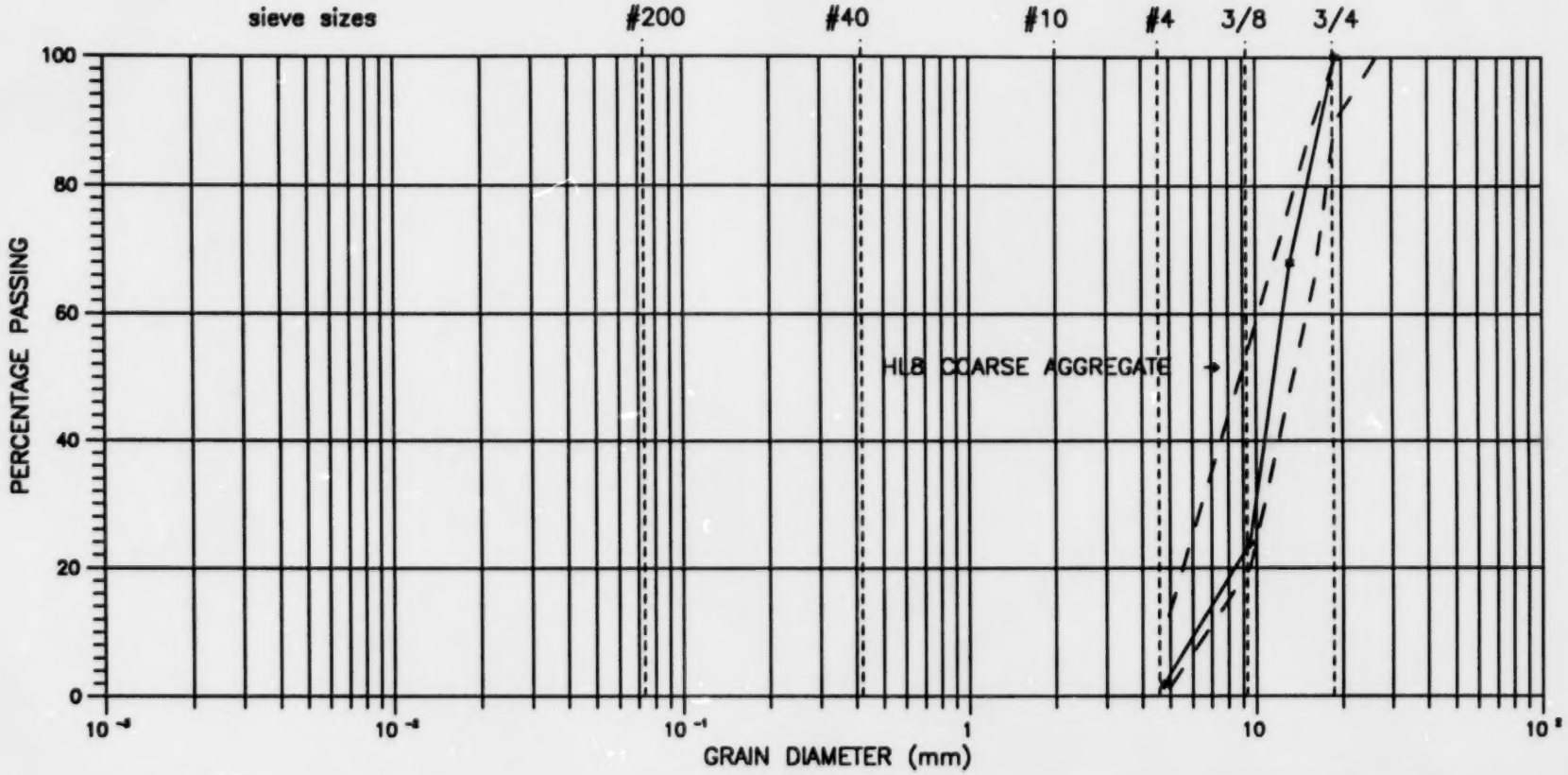
MECHANICAL ANALYSIS – PIONEER , NICKEL CENTRE – HL8 COARSE AGGREGATE



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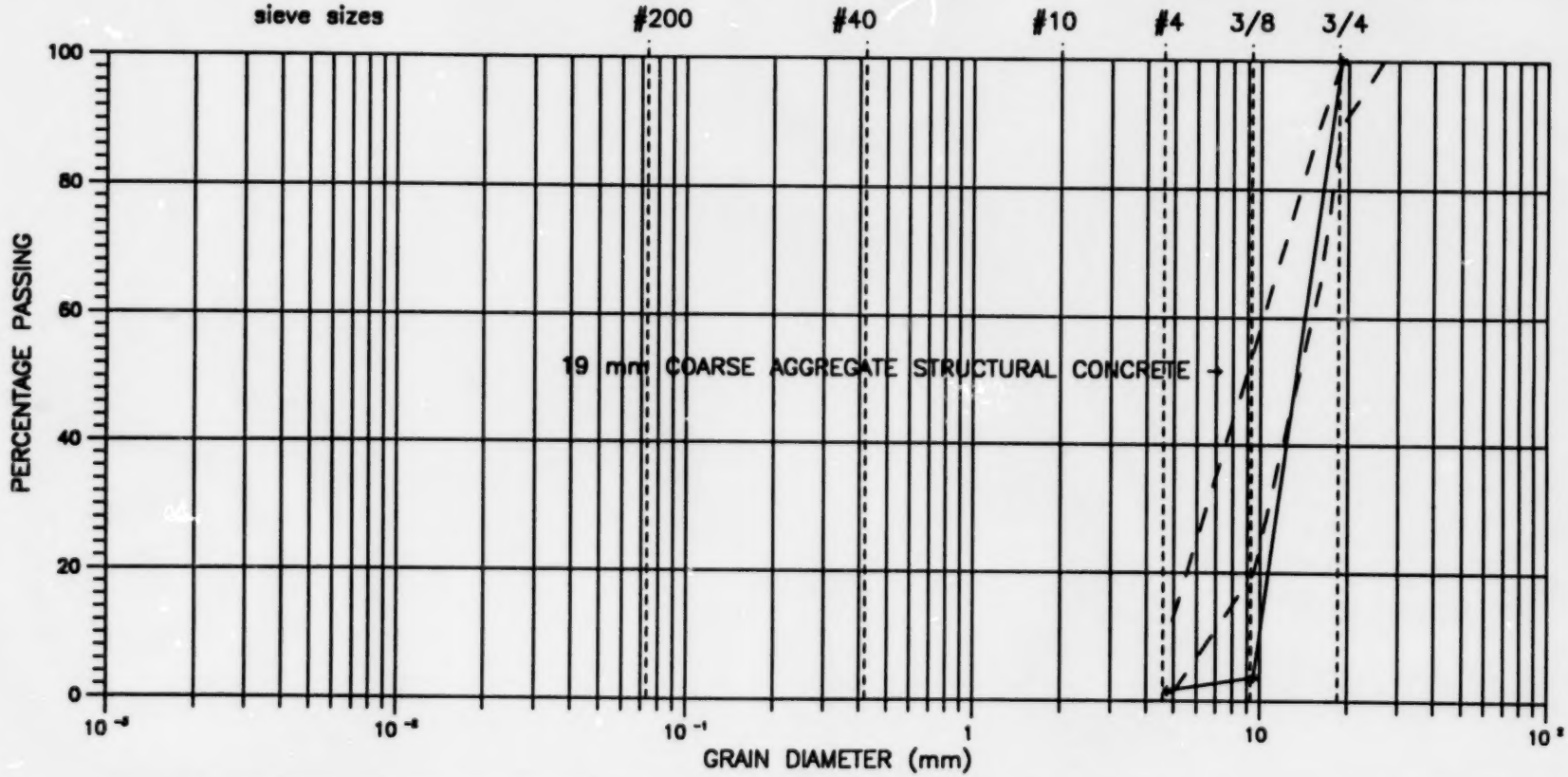
RESEARCH DIVISION

91-207

MECHANICAL ANALYSIS – NORFOLK QUARRY – HL8 COARSE AGGREGATE



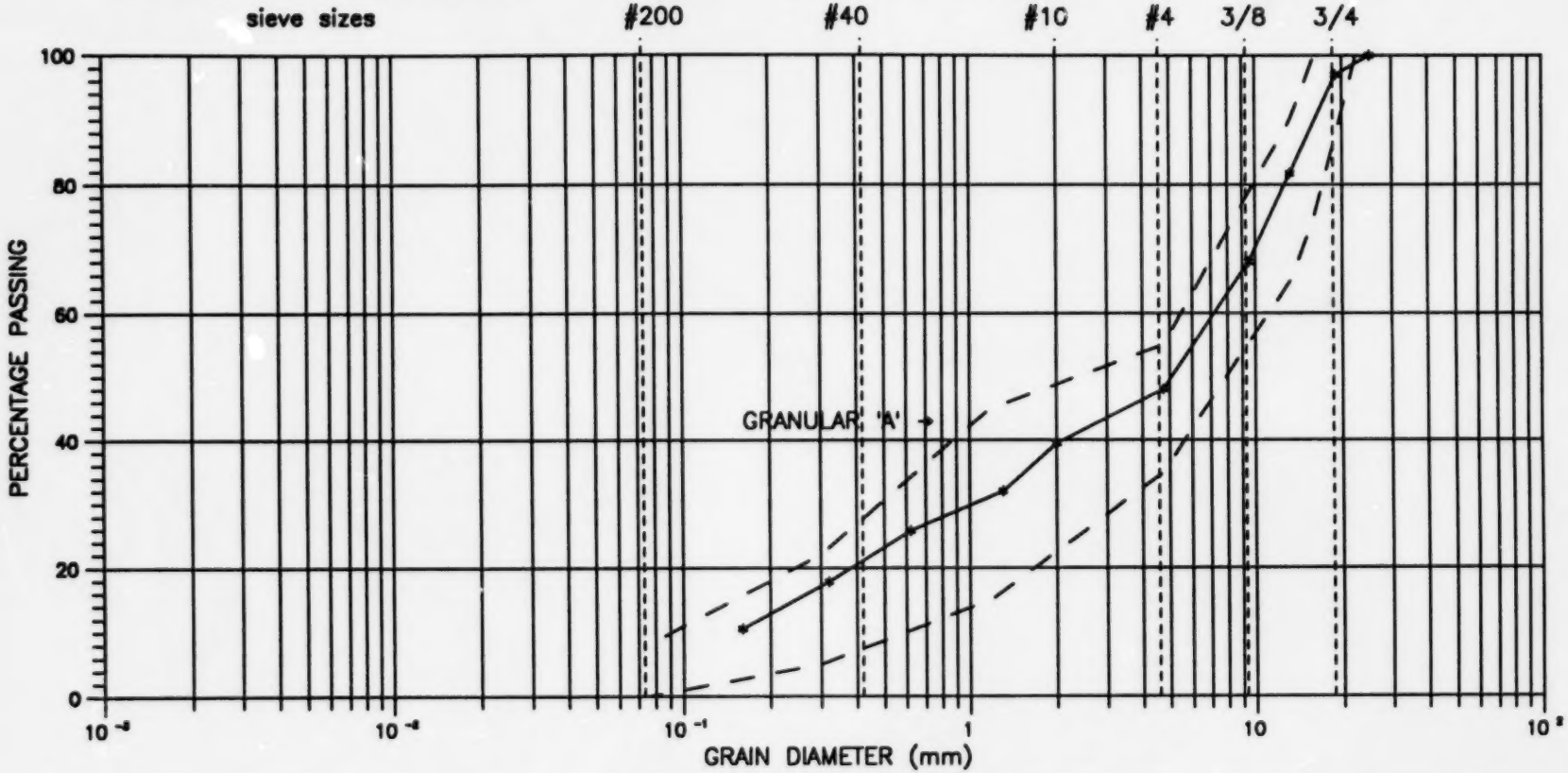
clay	to silt	sand			gravel	
		fine	medium	coarse	fine	coarse

unified soil classification

◆◆◆◆◆ ELECTRICAL RESISTIVITY = 13,818 ohm–m

ONTARIO HYDRO
RESEARCH DIVISION

MECHANICAL ANALYSIS – DICK CONSTR. BOLTON – GRANULAR A'



clay	to silt	sand			gravel	
		fine	medium	coarse	fine	coarse

unified soil classification

– — ELECTRICAL RESISTIVITY = 1043 ohm–m

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RESEARCH DIVISION

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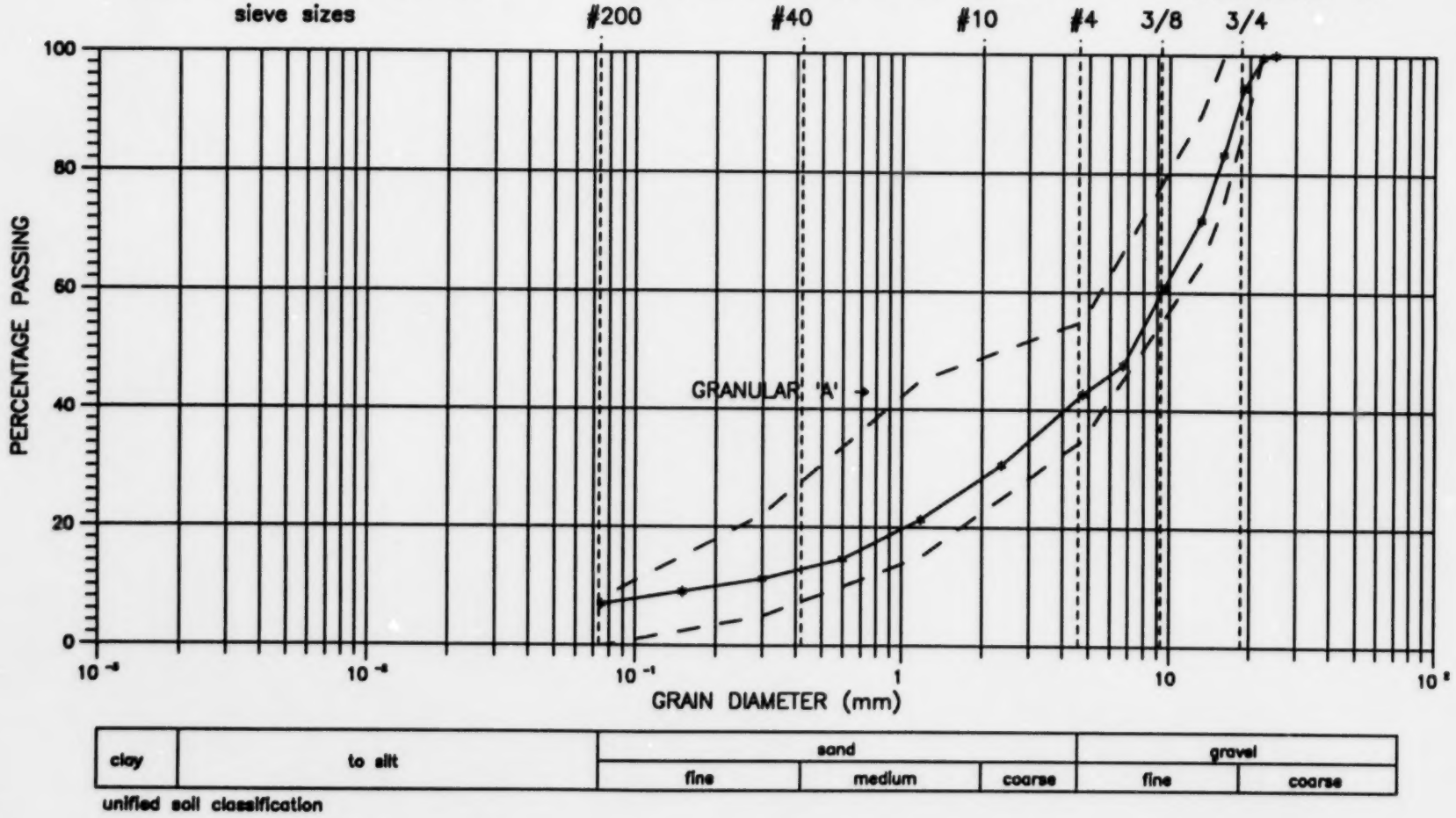
MECHANICAL ANALYSIS – DUFFERIN AGG. MILTON – GRANULAR 'A'



– — ELECTRICAL RESISTIVITY = 532 ohm–m

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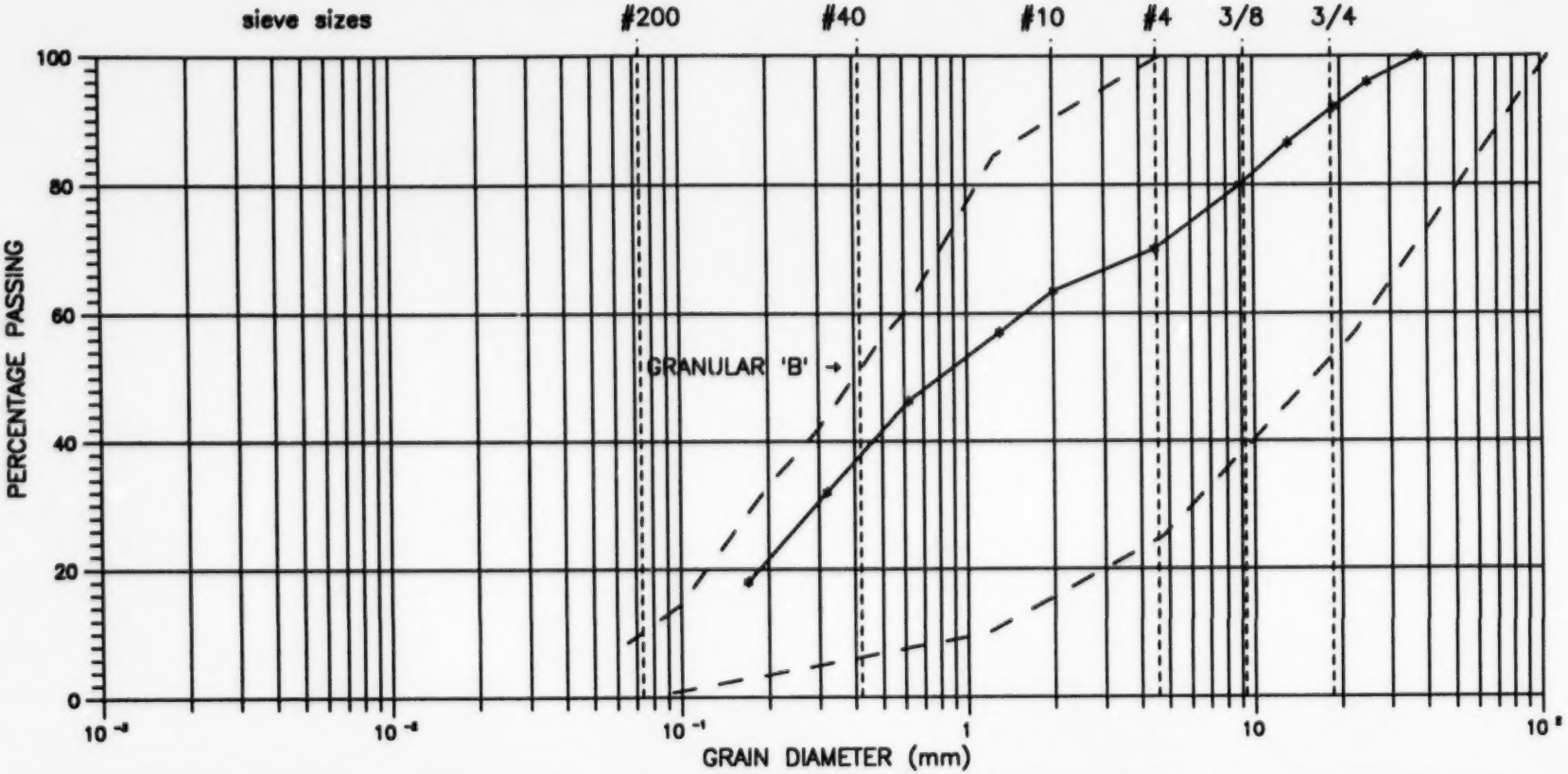
MECHANICAL ANALYSIS – DICK CONSTR. BOLTON – GRANULAR B'



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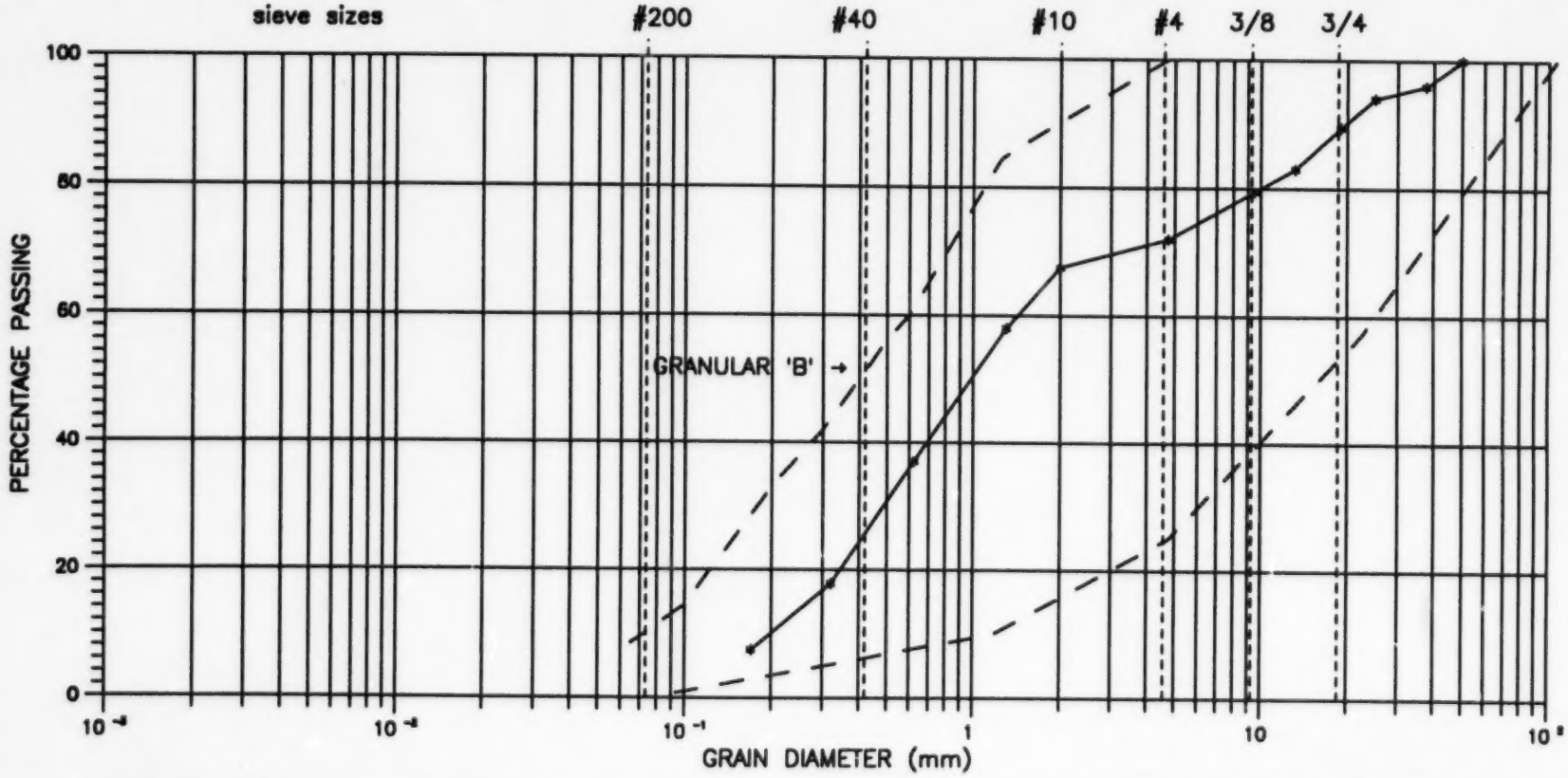
MECHANICAL ANALYSIS – FRANCESCHINI AGG. BRAMPTON – GRANULAR 'B'



clay	to silt	sand			gravel	
		fine	medium	coarse	fine	coarse

unified soil classification

◆◆◆◆◆ ELECTRICAL RESISTIVITY = 514 ohm-m

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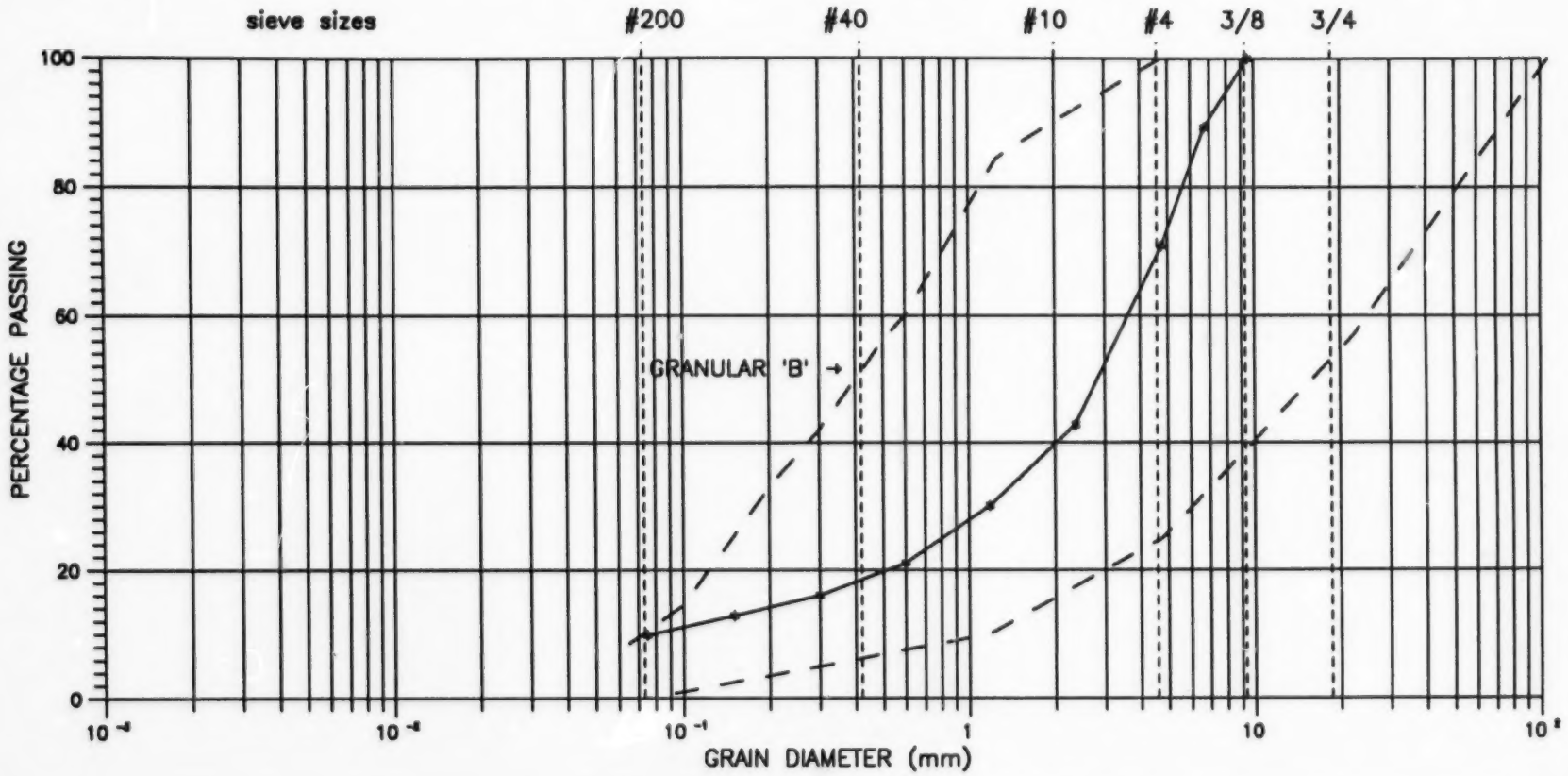
RESEARCH DIVISION

MECHANICAL ANALYSIS – DUFFERIN AGG. MILTON – GRANULAR 'B'



●●●●● ELECTRICAL RESISTIVITY = 484 ohm–m

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